SULFATE RELEASE FROM THE USX TAILINGS BASIN AND QUANTIFICATION OF SULFATE SOURCES

FINAL REPORT

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1. INTRODUCTION

Seepage from the USX tailings basin has resulted in elevated sulfate concentrations in the Sand River and the Dark River, which receive this seepage. The Sand River has stands of wild rice and is categorized as Class 4A, "waters of agricultural and wildlife use", by the Minnesota Pollution Control Agency (MPCA). A sulfate standard of 10 mg/L is "applicable to water used for production of wild rice during periods when the rice may be susceptible to damage by high sulfate levels" (Strudell, 1990). Since sulfate concentrations considerably above this level have been observed in the Sand River, a monitoring program was established by USX and the Minerals Division of the Minnesota Department of Natural Resources (MDNR) to evaluate sulfate release from the tailings basin. Subsequently the MDNR and the U. S. Bureau of Mines signed a cooperative agreement (CO299003) to integrate sulfur balance data collected by USX with the field data collected by the MDNR.

The objective of the field study conducted by the MDNR was to quantify the sulfate release from the basin. The objective of the sulfur balance study conducted by USX was to identify the sources of sulfate and quantify the magnitude of release from these sources. The second study is of interest for determining the sulfate release after site closure. Of particular interest is the sulfate contribution resulting from oxidation of iron sulfides present in the tailings. This oxidation will continue to release sulfate after closure of the operation. Consequently, the basin reclamation must be designed with the consideration of meeting water quality standards.

2. SITE DESCRIPTION

The Minntac taconite mine and plant in Mountain Iron, Minnesota, has been in operation since 1966, and is presently operated by USX Corporation (formerly U.S. Steel). Construction of the USX tailings basin began with the 1966 construction of the starter dike in cell 1. The basin has a present perimeter of 21.8 km (kilometers, 13.6 miles) and covers 36 km^2 (14 mi^2 or 8972 acres; USX, 1987). The U.S. Army Corps of Engineers (1979) reported a storage volume of 5.703×10^8 m^3 (462,370 acre-feet). The tailings basin is located north of the Laurentian divide and drains to two watersheds. Seepage from the basin flows west to the Dark River and subsequently into the Sturgeon River after approximately 27 km (17 miles). Seepage also flows east through the Little Sandy and Sandy Lakes (Twin Lakes) and down the Sand River (figure 1). After about 20 km (12 miles) the Sand River joins the Pike River, which drains into Lake Vermilion.

MDNR Fish and Wildlife Division, Wildlife Section, conducted a game lake survey on Sandy and Little Sandy Lakes in 1966 and July 21, 1987. Water levels in the lakes were approximately 0.61 m (2 feet) higher in 1987 compared to 1966; water clarity increased from 0.40 m (1.3 feet) in 1966 to 1.8 m (6 feet) in 1987; and aquatic vegetation changed very little except that wild rice was absent from both lakes in 1987. In a good year, these lakes have approximately 80 ha (200 acres) of wild rice (McHugh, 1987). The wild rice crop in the two lakes was good in 1970 and 1972, fair in 1966, 1968, 1973, 1980, 1981 and poor in 1977, 1978, 1982, 1984 through 1987. The extent of the wild rice crop was not documented in 1967, 1969, 1971, 1974, 1975, 1976, or 1979 (McHugh, 1987).

In good years a 16 to 20 ha (40 to 50 acres) area of wild rice grows in a wide spot in the Sand River just upstream of Trunk Highway (TH) 169. The crop was good in 1984, 1985, and 1987 and poor in 1986 (McHugh, 1987).

3. METHODS

3.1. Stream Monitoring

On fourr occasions between March 4 and July 16, 1987, the MDNR sampled sulfate and specific conductance at several sites on the Dark and Sand Rivers and their tributaries (Lapakko et al., 1988). Results from this survey indicated that sulfate concentrations decreased as the distance downstream from the tailings basin increased. This is consistent with dilution by tributaries downstream of the tailings basin. Sulfate concentrations in one tributary to the Dark River and four tributaries to the Sand River were less than 8 mg/L. Comparison of these values with those observed in the Dark and Sand Rivers indicated that release of sulfate-rich water from the tailings basin was the major sulfate contributor to these receiving waters. Based on the stream survey, previous data, the existing USX sampling program, and the amenability of sites to flow gaging, two stations were selected for more extensive water quality sampling and discharge gaging by the MDNR (Lapakko et al., 1988).

On the Dark River a station was established at Forest Road (FR) 271, which is 21.6 km (13.5 miles) downstream from the western tailings basin seepage (figure 1). The stream at FR 271 was shallow and the current was relatively fast, making the site conducive to gaging. In addition, the site had been gaged previously by the USGS and USX.

On the Sand River a station was established at TH 53, which is 8.3 km downstream from the eastern edge of the tailings basin. At TH 53 the channel was fairly deep and, due to the large cross-sectional channel area, the velocity of flow was slow, lending to error at low flows. Since considerable historical data were available for the TH 53 site, it was established as the primary sampling site on the Sand River.

From July 16, 1987 through December 1989, at intervals of two to four weeks, the primary stations were sampled for sulfate concentration and specific conductance and gaged for flow. A schedule was established for the DNR and USX to sample on alternate weeks, thereby optimizing data collection. The MDNR sampling ceased in August 1988, and subsequent sampling was done solely by USX. Flow was measured using a Pygmy meter and methods described by Buchanan and Somers (1969), and grab samples were collected for water quality analysis. Specific conductance was measured using a Myron L conductivity meter, and sulfate was analyzed using the barium sulfate turbidimetric technique (APHA et al., 1975).

3.2. Tailings Basin, Seep, and Well Monitoring

The tailings basin water quality in cells 1 and 2 was typically measured one to three times annually. Samples for cell 1 were collected at the return water intake for the plant, while samples for cell 2 were taken at the culvert between cells 1 and 2. Two seeps from the tailings basin, the east toe and west toe seeps (figure 2), were monitored by USX for sulfate and flow. These sites were monitored for sulfate concentration and specific conductance five times from August 1987 through January 1988. Sulfate concentration, specific conductance, and flow were determined at least twice monthly from February 1988 through November 1989. Nine other seeps were monitored in 1987 for water quality only. Ten wells around the basin (figure 2) were monitored once or twice annually by USX.

3.3. Sulfur Balance for the Plant

To quantify the sulfate input to and output from the plant, USX conducted a sampling program from January 22 through February 16, 1990 (appendix 4). For purposes of this discussion the major inputs measured were categorized as pellet-related solids (crude ore, dolomite/limestone, bentonite), water (tailings basin return water and make-up water), and fuel (natural gas, coal/coke, and wood). The major outputs measured were similarly categorized as pellet-related solids (pellets, fine and coarse tailings, dust from dust collectors, sweeping residues from the plant), water (with tailings and pellets, and from wet dust collector, agglomerator, concentrator, tailings pocket, pellet stockpile, sewage treatment, and steam out the stack), and fuel output with waste gas.

4. RESULTS AND DISCUSSION

4.1. Sulfate Release to the Sand and Dark Rivers

The sulfate mass release from the tailings basin was calculated as the sum of the mass release to the Sand and Dark Rivers. The mass release in each river was calculated based on the sulfate concentration and flow measured during each sampling event. The sulfate flux for each event was calculated as the product of the sulfate concentration and flow. The sulfate mass release between two sampling events was calculated as the product of the time elapsed and average of the two sulfate flux values. The values from each interval were summed to determine the total mass release.

The Sand River sampling site at TH 53 is approximately 8.3 km from the tailings basin. The period of record for this site was from December 22, 1987 to November 29, 1989. Over this period flow and sulfate concentration were measured 61 times. Flow ranged from 1 to 1700 L/s, with an average of 430 L/s (table 1). The average preoperational flow at TH 53 was estimated as 285 L/s based on the average flow for the Sand-Pike River near Embarrass, and the ratio of watershed areas for these two sites (data presented in appendix 3 of MN DNR, 1987). Sulfate concentrations ranged from 37 to 370 mg/L, as compared with 1.8 to 12 mg/L for the preoperational phase (appendix 4 in MN DNR, 1987).

The sulfate concentration at TH 53 exceeded the MPCA Class 4A sulfate standard (10 mg/L) 100 percent of the time. The Sandy and Little Sandy Lakes produce 80 ha (200 acres) of wild rice in a good year (McHugh, 1987), and are upstream of TH 53 and downstream of the tailings basin. Consequently, the sulfate concentrations in these lakes were higher than at TH 53, and also exceeded the sulfate standard.

In good years 16 to 20 ha (40 to 50 acres) of wild rice grow in the Sand River just upstream of TH 169. Sulfate concentration was not measured at this site during the present study, however on March 4, 1987 the sulfate concentration was 60 percent of that at TH 53. Assuming this factor was constant over time and using it to estimate the downstream concentration, yields a range of 22 to 220 mg/L for the area upstream of TH 169. Thus, it is likely the sulfate concentrations at this site also exceeded the water quality standard.

Variations in flow strongly influenced the sulfate flux at TH 53, as indicated by data from 1988 (figure 3). This suggests that at high flow the sulfate flux reflects the release of sulfate stored in the Sandy and Little Sandy Lakes and/or the wetland between the tailings basin and the monitoring station. The total sulfate release from December 22, 1987 through November 29, 1989 was 3300 metric tons (mt), which represents a release rate of 1670 mt/year. This long-term rate more accurately reflects the sulfate release from the tailings basin. Rates determined over shorter time periods will be more greatly influence by sulfate release from, or addition to, storage between the tailings basin and the monitoring site.

The Dark River sampling site at FR 271 is about 21.6 km from the west toe of the tailings basin. The period of record for this site was from September 22, 1987 to December 14, 1988. Over this period flow and sulfate concentration were measured 42 and 46 times, respectively. Flow ranged from 28 to 2200 L/s, and averaged 440 L/s (table 1). The preoperational average flow at this site was 1030 L/s (appendix 1, MN DNR, 1987). Sulfate concentrations ranged from 12 to 150 mg/L as compared to a range of 6.5 to 14 mg/L during the preoperational phase (appendix 2, MN DNR, 1987). As was the case for the Sand River, the sulfate flux was highly dependent on flow (figure 4). The total sulfate release over this period was 1670 mt, which represents a release rate of 1360 mt/year.

Although the periods of record for the two rivers were not the same, the interval between December 22, 1987 to December 14, 1988 was common to both. The mass sulfate released to each river over this period was 1360 mt, for a total release from the basin of 2720 mt over the 358-day interval (table 1). This represents an average release from the tailings basin of approximately 2800 mt/year. The data also indicate that the release from the basin is fairly evenly divided between the two watersheds.

The release rate for the Sand River from December 1988 through November 1989 was 1960 mt/year, or roughly 40 percent higher than for the previous year (table 1). This increase was the combined result of a 30 percent increase in flow (average flow increased from 380 to 490 L/s), and an 8 percent increase in sulfate concentration. Assuming release to the Dark River equalled that to the Sand River, as was the case the previous year, yields a sulfate release rate of roughly 3900 mt/year from the tailings basin. Thus, for intervals covering an entire year, the sulfate release from the tailings basin ranged from a measured value of 2800 mt/year to an estimated 3900 mt/year.

The increase in sulfate release from 1988 to 1989 may have been the result of increased sulfate concentrations in the tailings basin seepage. The rate of sulfate release from the basin is determined by the sulfate concentration of the seepage and the seepage rate. The average tailings basin sulfate concentration in 1988 was 300 mg/L (n=2), while that in 1989 was 530 mg/L (n=6, appendix 5). Seepage flow rates measured in 1988 and 1989 were not highly variable. The rate of seepage is proportional to the head differential between the water level in the tailings basin and that outside the basin (assuming flow is generally consistent with the Darcy equation and the length of the flow path is relatively constant). Since the head differential is fairly constant, a relatively constant rate of seepage would be expected.

In 1988 the average sulfate release rates from the east and west seeps were 154 and 46 mt/year, respectively. In 1989 the corresponding sulfate release rates were 162 and 90 mt/year. These values indicate that these two major seeps contributed about seven percent of the total sulfate observed in the rivers. Additional sulfate release from the basin occurs from other small seeps (appendix 2, table A2.3) and with deeper ground water flow. Elevated sulfate concentrations in wells around the tailings basin (appendix 3) support the contention of sulfate release with deeper ground water flow.

4.2. Sulfur Balance for the Plant

The total sulfur input for the sampling period was 4066 mt (4482 st). The dominant sulfur input occurred with the pellet-related solids, particularly the ore, which contributed 80 percent of the input sulfur. The total mass of pellet-related solids was 3.55 million mt (3.91 million st), which contained 3230 mt (3560 st) of sulfur (table 2). The second highest sulfur input was with water, which contributed roughly 14 percent (table 3), as compared to approximately 5 percent for fuel and lubricant (table 4).

It was necessary to estimate the volume of return water input, since this flow was not adequately metered. The estimate was based on the assumption that the input volume equaled the total output volume (see table 8). The return water input volume was then calculated as the difference between the total output volume and the volume of make-up water from the Mountain Iron pit.

The total sulfur output from the plant during the sulfur balance study was 4076 mt (4493 st). As with the input, the pellet-related solids comprised the majority of the plant output, both in total mass and sulfur content (table 5). These solids include the pellets, fine tailings, coarse tailings, dust from dust collectors within the plant, and "sweeping residues" from the plant. The total mass of these outputs was determined to be 3.37 million mt (3.71 million st), with a sulfur content of 3350 mt (3690 st, table 6). This represents a 5 percent loss of solids and a sulfur gain of less than 4 percent (table 6).

The major water outputs during the study were water with the tailings, and water from the agglomerator and concentrator (table 7). The mass of sulfur in the output water was 688 mt (758 st), or 119 mt (131 st) more than that associated with the input. All of the water output was to the tailings basin, with the exception of small outputs of steam out the stack and water contained in the pellets. The sulfur output to the basin exceeded the input from the basin by 273 mt (688 - 415 = 273, table 8). The waste gas output contained 40 mt (44 st) of sulfur (table 9). The input and output sulfur values for the three different categories are summarized in table 10.

Given the potential for error in measuring the millions of tons of solids, it is assumed that the mass output equalled the mass input. Similarly it is assumed that sulfur was conserved in the solid phase. This seems quite reasonable since any sulfur transfer would be to the water phase and this transfer would be minimal. The sulfur associated with the pellet-related solids input is present as sulfide in pyrite. Since the oxidation rate of fresh pyrite is quite slow and the contact time between the solids and the water in the plant is relatively short, little release of sulfate from the solids would be expected.

Assuming that sulfur was not released from the pellet-related solids, the net sulfur input of 273 mt to the tailings basin would be the result of sulfur addition with the make-up water and transfer from fuel to the water phase. The make-up water from the Mountain Iron pit contributed 154 mt of sulfur (table 8) which implies a contribution of 119 mt from the fuel. The input and output values are based on discharge measurements of millions of cubic meters of flow and sulfate analysis of grab samples. Although the results appear generally reasonable, they may lack the resolution necessary to determine the sulfur input from the fuel phase.

There are three alternatives for quantifying the amount of sulfur transferred from the fuel to the water phase. Assuming all sulfur present in the fuel is gassified, it either reports as waste gas or is removed by the wet scrubber. The scrubber water then reports to the tailings basin. The amount of sulfur transferred to the water phase can be calculated as the difference between the sulfur present in the fuel and the sulfur measured in the waste gas. Second, the sulfur transfer from the fuel to the water phase can be quantified based on the scrubber flow rate and the scrubber input and output sulfate concentrations. Third, the sulfur transfer can be estimated based on the total sulfur content of the fuel and typical efficiencies of scrubbers used in similar situations.

Assuming all of the 264 mt (291 st) of sulfur present in the input fuel was converted to gas and 40 mt reported as waste gas (table 9), 224 mt (247 st) of sulfur were removed by the scrubber (264 - 40 = 224). This represents an 85 percent efficiency for sulfur removal by the scrubber. This is well above the expected efficiency of this type of system, which is in the range of 25 to 50 percent and typically between 25 and 33 percent (Beil, 1990). Due to the large discrepancy between the calculated efficiency and the expected efficiency, the accuracy of the waste gas measurement is in question.

The sulfur transfer from the fuel to the water based on measurements taken at the scrubber yielded an efficiency which was more consistent with previously observed values. The sulfate concentration of the scrubber water input averaged 436 mg/L as compared to an output value of 656 mg/L. Multiplying this change in concentration by the 378.5 L/s (6000 gpm) scrubber flow for 25 days, yields a value of 60 mt (66 st) of sulfur transferred from the fuel to the water. (Note that the sulfur concentration is one-third the sulfate concentration.) This measurement yields an efficiency of roughly 23 percent, only slightly below the expected range. However, the sulfur released with the waste gas would be 204 mt (225 st), which is in conflict with the 40 mt value measured. The accuracy of the waste gas sulfur measurement should be examined in the future.

As previously mentioned, the expected efficiency of the scrubber is in the range of 25 to 50 percent, with typical values in the range of 25 to 33 percent (Beil, 1990). Using the overall range yields a sulfur transfer to the water phase of 66 to 132 mt. The sulfur transfer was also calculated for efficiencies of 29 percent (the mean of the typical range) and 33 percent. These values as well as those calculated based on the water balance, waste gas measurement, and scrubber data are presented in table 11.

To summarize the sulfur balance for the plant, it is concluded that sulfur in the pellet-related solids is conserved, sulfur is added to the tailings basin in make-up water from the Mountain Iron pit, and that there is a transfer of sulfur from the fuel to the water. The water balance indicated that the sulfur contributions from make-up water from the Mountain Iron pit and fuel were 154 mt and 119 mt, respectively, during the sulfur balance study. The accuracy of the contribution with make-up water during the study is questionable due to the necessary estimation of the flow from the tailings basin to the plant and the potential error in the large flow measurements. Modification of the distribution of the input flow between the tailings basin return water and make-up water can significantly alter these values, as well as the net sulfur input to the tailings basin. More accurate measurement of both return and make-up water would decrease this uncertainty.

Measurement of waste gas output yielded a transfer of 224 mt sulfur from the fuel to the water phase during the period of measurement. This value is questionable since it yields a scrubber efficiency well above that commonly observed. Measurements focused on the scrubber flow and water quality yield a value of 60 mt sulfur transferred from the fuel to the water. Assumed scrubber efficiencies of 25 to 50 percent yielded sulfur transfer masses of 66 to 132 mt during the sulfur balance study.

4.3. Sulfate Storage in the Tailings Basin

The mass of sulfate present in the open water area of each basin cell was calculated as the product of the volume of water in the cell and the associated sulfate concentration of the water. These two sulfate masses were summed to determine the mass of sulfate present in the open water areas of the tailings basin. Sulfate storage in the interstitial water held in the tailings was not considered. The sulfate concentrations in the cells were measured from one to three times annually. In cell 1 the concentration was measured at the intake for the plant, while in cell 2 it was measured at the culvert between cell 1 and cell 2.

Due to spatial and temporal variations in sulfate concentration, the limited number of analyses at a single location in the cell may not be representative of the sulfate concentration in the entire cell over the course of a given year. The degree of spatial homogeneity would be affected by the retention time within a cell (determined by the water volume in the cell and the rate of appropriation for the plant), the balance of precipitation and evaporation, as well as the degree of mixing within the cell.

In particular, sulfate concentrations are likely to vary as a function of location in cell 2, which contains the majority of the tailings basin water (table 12). The highest sulfate concentrations would be near the tailings discharge, the location of which varied during operation. Cell 2 samples were taken at the culvert between cell 1 and cell 2, toward the east side of the basin. If the tailings discharge were close to the culvert, the sulfate concentrations at the culvert would tend to overestimate the average concentration in the basin. Similarly, when the tailings discharge was relatively distant from the culvert, the average basin concentration would be underestimated by samples taken at the culvert.

By using data for a period of several years, the variations in the measurement of sulfate concentration in the basin would tend to balance out. The sulfate concentration in the tailings basin water increased steadily over time, as did the volume of water in the basin (table 12). This indicates a continual increase in the amount of sulfate in the basin, as is depicted in figure 5. Linear regression analysis of the data from 1982 through 1988 indicates an increase of 3200 metric tons of sulfate per year in the tailings basin ($r=0.928$, $n=7$). The sulfate mass in 1989 was inconsistent with the variation observed in previous years. When the 1989 value is included in the linear regression, an increase of 4900 mt of sulfate per year is calculated ($r=0.774$, $n=8$).

4.4. Calculation of Sulfate Release from the Tailings

The change in the mass of sulfate stored in the basin is the difference between the sulfate input to the basin and the sulfate output from the basin. The sulfate input includes the sulfate present in make-up water from the Mountain Iron pit, sulfate from the stack scrubber, and the input due to oxidation of sulfide minerals in the tailings. The sulfate output is the sum of outputs to the Sand River and the Dark River.

$$I_T + I_P + I_F - (O_S + O_D) = \Delta S \qquad (1)$$

where I_T = sulfate input to the basin due to oxidation of sulfide minerals in the tailings;
I_P = sulfate input to the basin from the Mountain Iron pit;
I_F = sulfate input to the basin from the stack scrubber;
O_S, O_D = sulfate outputs from the basin to the Sand River and Dark River, respectively; and
ΔS = the change in sulfate storage in the basin.

The value for the input due to oxidation of sulfide minerals present in the tailings is the only value which has not been quantified and can, therefore, be determined as follows.

$$I_T = \Delta S + (O_S + O_D) - I_P - I_F \qquad (2)$$

The values determined for the change in storage were 3200 to 4900 mt sulfate per year, depending on the period over which the linear regression was conducted. Two values were determined for the sulfate output from the basin to the Sand and Dark Rivers. Based on one year of monitoring, the combined output to the two rivers was 2800 metric tons per year in 1988. Only the Sand River was monitored during 1989 and, assuming equal release to both rivers, the total output was 3900 metric tons per year. Both of these values will be considered in the calculation of the sulfate input from the tailings.

The input from the Mountain Iron pit from 1982 through 1988 was determined based on the volume of make-up water appropriated and a calculated sulfate concentration. The sulfate concentration of the pit water was measured as 236 mg/L in 1987, and four samples taken during the sulfur balance study averaged 253 mg/L (1/22/90 -2/16/90). The annual rate of change in the sulfate concentration over this period was 6.4 mg\L. Assuming this rate was constant from 1981 to 1989, and using the 1987 value as a bench mark, the sulfate concentrations for the period were calculated. These concentrations were multiplied by the volume of water appropriated to determine the annual sulfate mass input from the Mountain Iron pit. From 1982 to 1988 the values ranged from 500 to 3330 metric tons per year and averaged 1620 t/yr (table 13).

The sulfate input from the stack scrubbers was calculated based on fuel use and composition data obtained from USX. It was assumed that all sulfur present in the fuel was converted to sulfate and that the scrubbers were 25% efficient. This is close to the efficiency measured based on the stack scrubber water flow rate and the difference between the sulfate concentrations in the scrubber water input and output water (see section 4.2, paragraph 10). It is also at the lower end of the expected scrubber efficiency. Using the 25% efficiency and the data on fuel mass and sulfur content for 1982 to 1988, the annual scrubber sulfate inputs to the basin ranged from 270 to 1260 metric tons, with an average of 810 metric tons (table 14).

The annual sulfate input due to oxidation of sulfide mineral present in the tailings was calculated using the aforementioned values in conjunction with equation 2. Two values were used to represent both the change in storage (3200 and 4900 metric tons per year) and the sulfate release to the Sand and Dark Rivers (2800 and 3900 metric tons per year). The change of sulfate storage is the least accurate of the values. Average values from 1982 to 1988 were used for the annual input from the Mountain Iron pit (1620 metric tons) and the scrubbers (810 metric tons).

The four calculations yielded annual sulfate inputs of 3570 to 6370 metric tons from the tailings. These values represented 60% to 72% of the combined input from the make-up water, the scrubber, and the tailings. The use of average values and the change in storage over a period of seven years give a reasonable approximation of the sulfate contribution from the tailings.

The sulfate release due to oxidation of sulfides present in the tailings was also calculated using values measured directly from the beginning of 1988 through the end of 1989. The only shortcoming to this approach is that it places a high degree of confidence on the quantification of the sulfate storage based on individual measurements. The error inherent in this quantification would tend to increase when considering only two discrete values, rather than variations over a period of time (see section 4.3 and table 15).

From the beginning of 1988 through the end of 1989 the sulfate input from the Mountain Iron pit was fairly well quantified (5770 metric tons), the scrubber input was reasonably estimated (2790 metric tons), and the output to the Sand and Dark Rivers was measured (2800 + 3900 = 6700 metric tons). The change in storage was 22,800 metric tons (57,980 - 35,200 = 22,780 metric tons, table 12, table 15).

The calculated input from the tailings for the two years is 20,940 metric tons (22,800 + 6700 - 5770 - 2790 = 20,940), or an average of 10,470 metric tons per year. This is 71% of the total basin input over the two-year period. Although the mass of sulfate input calculated for tailings oxidation in this approach is roughly twice that from the previous calculation, the fraction of the total input is in the same range. It is possible that the extent of input from the tailings increased due to the relatively large input of additional tailings during this period.

5. CONSIDERATION OF THE SULFATE WATER QUALITY STANDARD

In the course of this evaluation, it is also necessary to ask if the present sulfate standard is excessively stringent for the protection of wild rice. Beaver activity and the associated fluctuations in water levels, climatological variables such as precipitation and temperature, and plant disease may also affect wild rice growth, but are not the focus of this discussion. In areas where wild rice is presently growing on the Sand River, the 10 mg/L sulfate standard for Class 4A waters is exceeded 100 percent of the time. At the Sand River site upstream from TH 169, good crops of wild rice were reported in 1984, 1985, and 1987. During these years, sulfate concentrations in the Sand River at TH 53 ranged from 40 to 340 mg/L. Assuming (as previously) that concentrations at TH 169 were 60 percent of those at TH 53, the sulfate concentrations in this area of wild rice were in the range of 24 to 200 mg/L. Despite the elevated concentrations, good wild rice yields were reported.

In the fall of 1988 the Eveleth Wildlife Office of the MN DNR seeded one 0.25 acre plot on both Sandy and Little Sandy Lakes with wild rice seed from Big Rice Lake (Lightfoot, 1990). Earlier in the year, beaver dams were removed and beaver trapped from the lakes to TH 53 to lower the water level. The wild rice seed germinated in both 1989 and 1990. The number of plants was greater in 1990 than 1989, although the crop was not harvestable (Lightfoot, 1990).

From 9/21/88 through 11/29/89 the sulfate concentration at TH 53 was analyzed 32 times and ranged from 60 to 305 mg/L, with an average of 152 mg/L. The sulfate concentrations in Sandy and Little Sandy Lakes were higher than these values, since the lakes are upstream of TH 53 and, therefore, receive less unimpacted water to dilute the tailings basin discharge. Despite concentrations well in excess of 10 mg/L, the wild rice was able to propagate.

The MPCA water quality standard for sulfate in areas of wild rice is based on observations by Moyle (1944) that in Minnesota, "no stands of rice occur in waters having a sulfate content greater than 10 mg/L, and rice is generally absent from water with more than 50 mg/L." Moyle and Krueger (1964) reiterated the 10 mg/L value but was less specific about the causal relationship between sulfate and toxicity:

> "In Minnesota the range is mostly limited to waters with concentrations of sulfate or "alkalai" salts lower than 10 parts per million of sulfate ion. Plantings of wild rice seed in prairie waters with higher concentrations of sulfates have generally failed. The westward and southern limit of the range in Minnesota follows the prairie edge, extending from Lake of the Woods and Red Lake southward through Detroit Lakes, thence across Ottertail County in an arc through the intervening counties to the Twin Cities area."

As was noted subsequently by the MPCA (1979), "These areas are confined to western Minnesota where soils developed from cretaceous shales and where evaporation exceeds precipitation." Furthermore these areas have elevated sulfur in the soil (Rehm et al., 1986). Thus, the reason wild rice was absent from the areas examined by Moyle (1944) and Moyle and Krueger (1964) may well have been the soil and/or the climate, rather than the sulfate present in the water. The sulfate may have been an indicator of the high sulfur soil, which was not conducive to wild rice growth, rather than a parameter toxic to wild rice.

This possibility is supported by several studies indicating the tolerance of wild rice to elevated sulfate concentrations. Wild rice has been grown in paddies where sulfate concentrations ranged from less than 4 to 156 mg/L (Grava and Koski, 1979; Grava, 1980, 1981). In commercial wild rice paddies along the Clearwater River, Trippler et al. (1977) reported sulfate concentrations of 22 to 390 mg/L, with an average of 170 mg/L.

Wild rice has also flourished in the presence of elevated sulfate concentrations in the natural environment. Based on observations of natural wild rice stands, Vicario and Halstead (1968) concluded that "The presence of large amounts of sulfate in the soil water [as high as 1500 mg/L] does not appear to be a deterrent to rice growth." Additional laboratory testing suggested that wild rice growth increased as aqueous sulfate concentration increased from 0 to about 250 mg/L.

Paulishyn and Stewart (1970) reported that, "Wild rice grows in a number of localities west of the Red River, which have relatively high sulfate concentrations. Such sites as Willowbend River, Jackson's Lake, Lake Kiche Manitou, LaSalle River and Sewell Lake have been analyzed for sulfate ion concentration and wild rice production." "West of the Red River, quantities of natural wild rice are found in waters containing up to 170 ppm sulfate ion concentration." They further noted that wild rice had been successfully transplanted into waters with sulfate concentrations as high as 150 mg/L.

Based on such observations, Lee and Stewart (1978) proposed that aqueous concentration limits for sulfate in areas containing wild rice should be increased or deleted. The fact that wild rice in the Sand River near TH 169 has grown well, despite elevated sulfate concentrations, further supports this proposal.

6. CONCLUSIONS

The data from monitoring the Sand River and Dark River clearly indicate that the sulfate release from the tailings basin has recently been in the range of 2800 to 3900 metric tons/year. This release has resulted in elevated sulfate concentrations in the Sand and Dark Rivers. The mass of sulfate stored in the tailings basin has also increased over time. The major sulfate sources are operational sulfate inputs from make-up water and stack scrubbers, and the oxidation of sulfate minerals present in the tailings. From 1982 to 1988 the operational sources contributed 1260 to 4590 metric tons of sulfate per year, with an average annual contribution of 2430 metric tons. From 1988 through 1989, when pellet production was higher, the annual operational contribution averaged 4280 metric tons over two years.

From 1982 to 1988 the average sulfate contribution by tailings oxidation was calculated as 3570 to 6370 metric tons of sulfate per year. From 1988 through 1989 the corresponding value was 10,500 metric tons per year. These values represent from 60% to 72% of the total sulfate contribution. Some of the sulfate input was manifested as increased sulfate storage in the tailings basin. It is likely that the oxidation of the tailings will continue long after the operation has closed, if appropriate mitigation measures are not taken.

In areas where wild rice is presently growing on the Sand River, the 10 mg/L sulfate standard for Class 4A waters is exceeded 100 percent of the time. If water quality standards are continually exceeded following the closure of the operation, post-closure remediation may be required. In the case of some abandoned operations, such remediation has been quite costly. For abandoned operations which generate acid drainage, remediation costs have run tens and even hundreds of millions of dollars (Biggs, 1990). The remediation costs for a problem of lesser environmental impact would be expected to be considerably lower, but could still be substantial. Thus, the sulfate release from the tailings and its impact on downstream water quality standards must be considered in the ultimate reclamation of the tailings basin.

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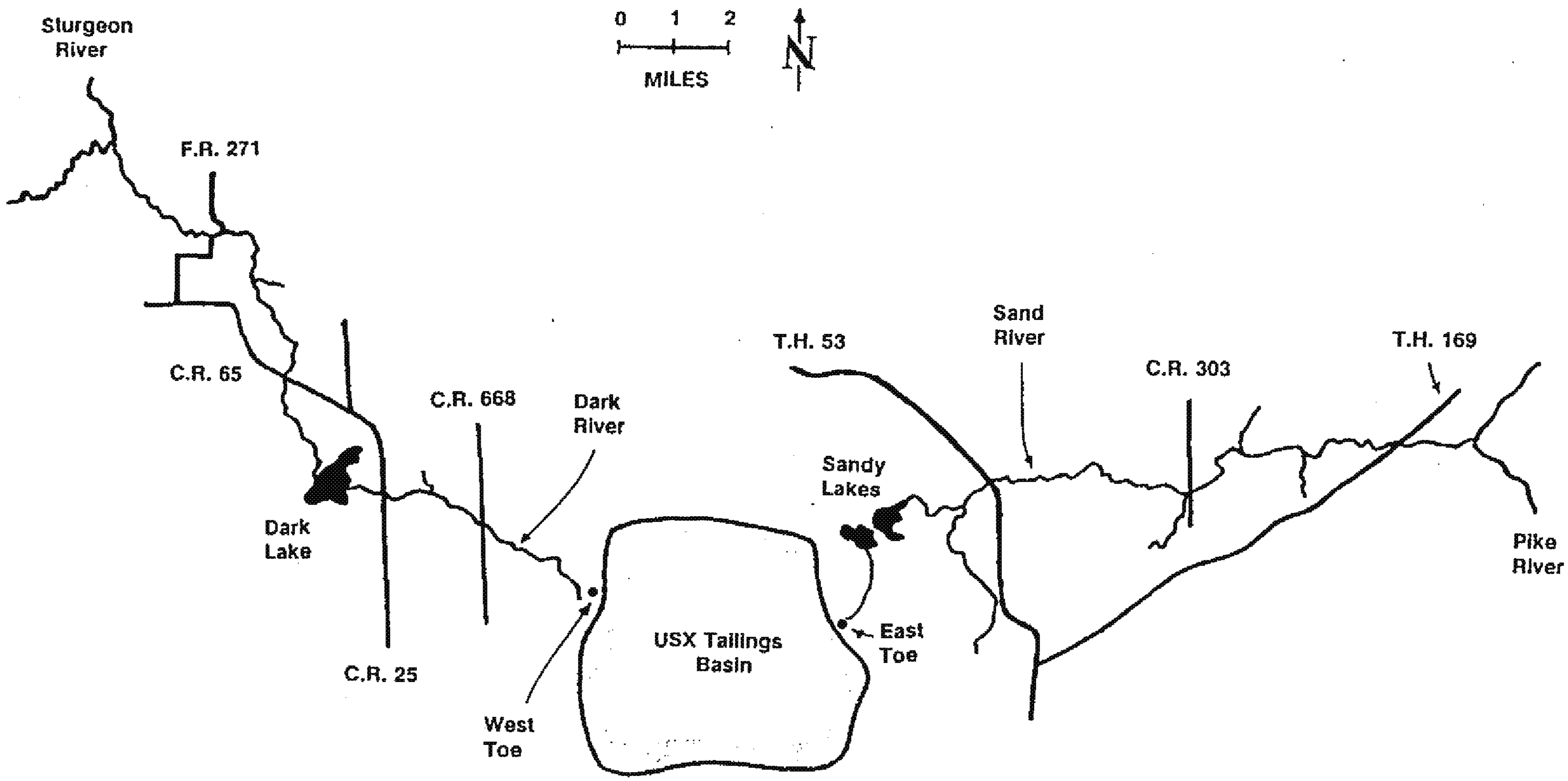

Figure 1. Map of Dark and Sand River Watersheds.

Figure 2. Wells and seeps around the USX tailings basin.

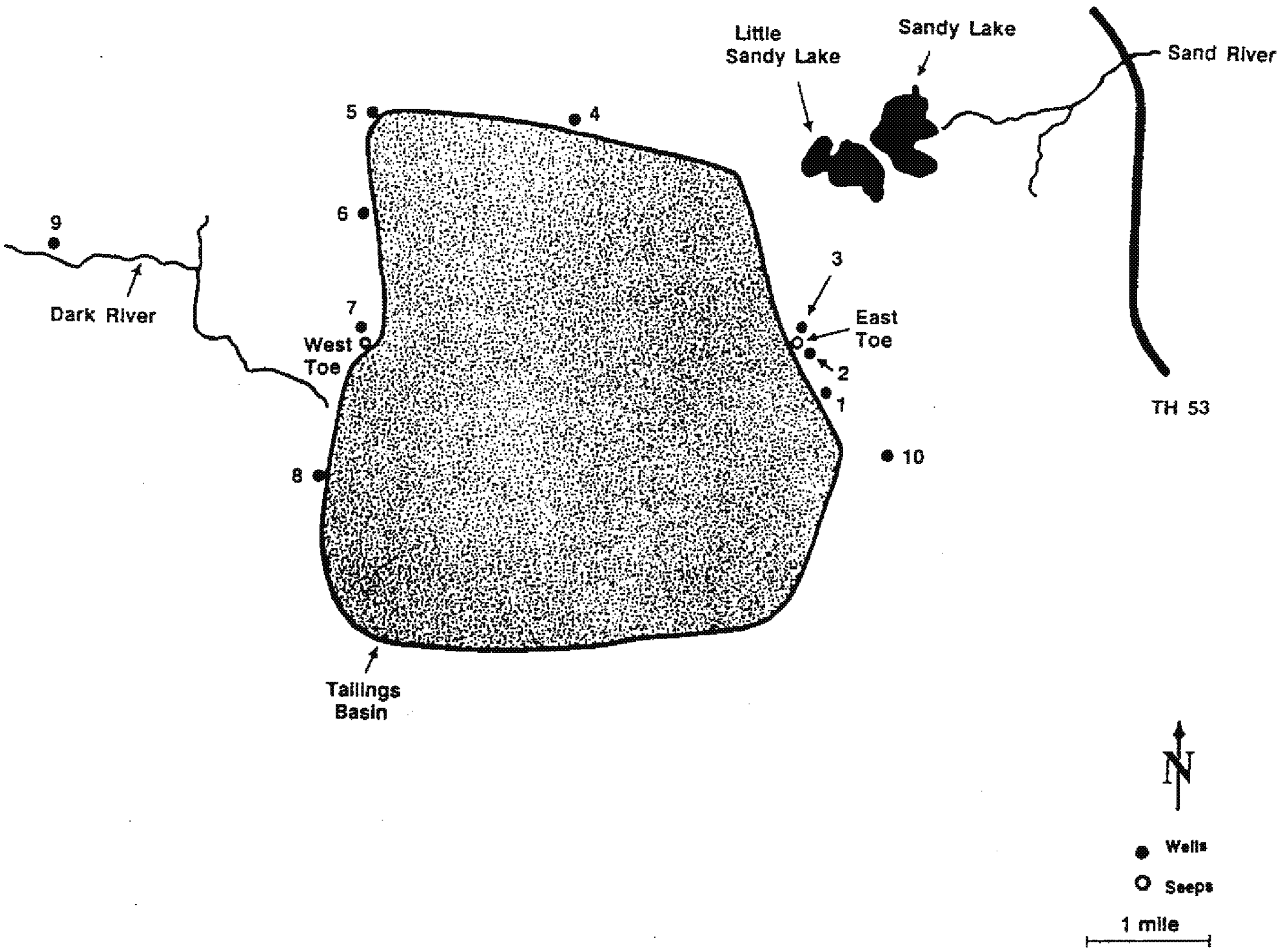

Figure 3. Sulfate flux and flow vs. time at TH 53.

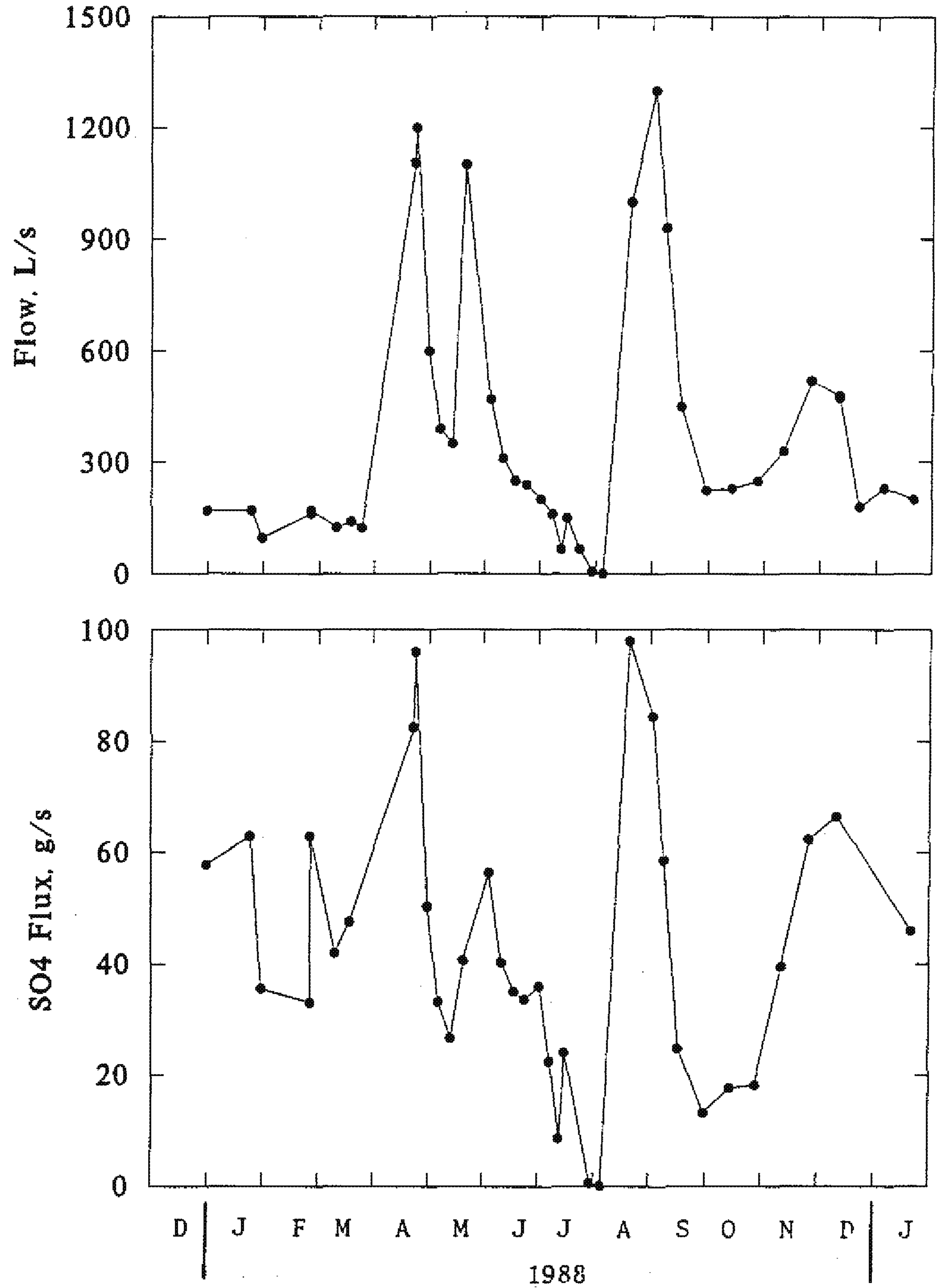

Figure 4. Sulfate flux and flow vs. time at FR 271.

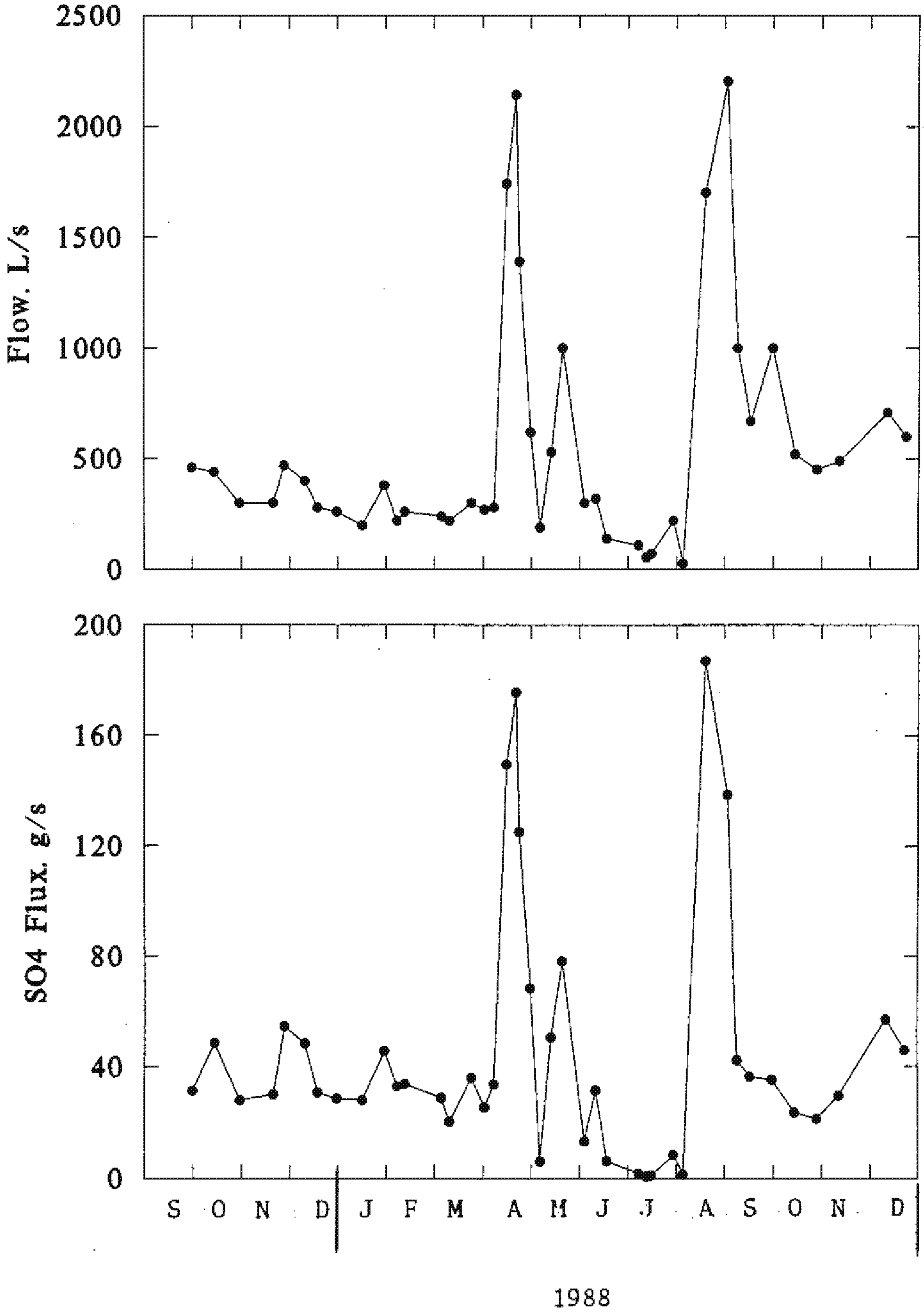

Figure 5. Sulfate mass in tailings basin over time.

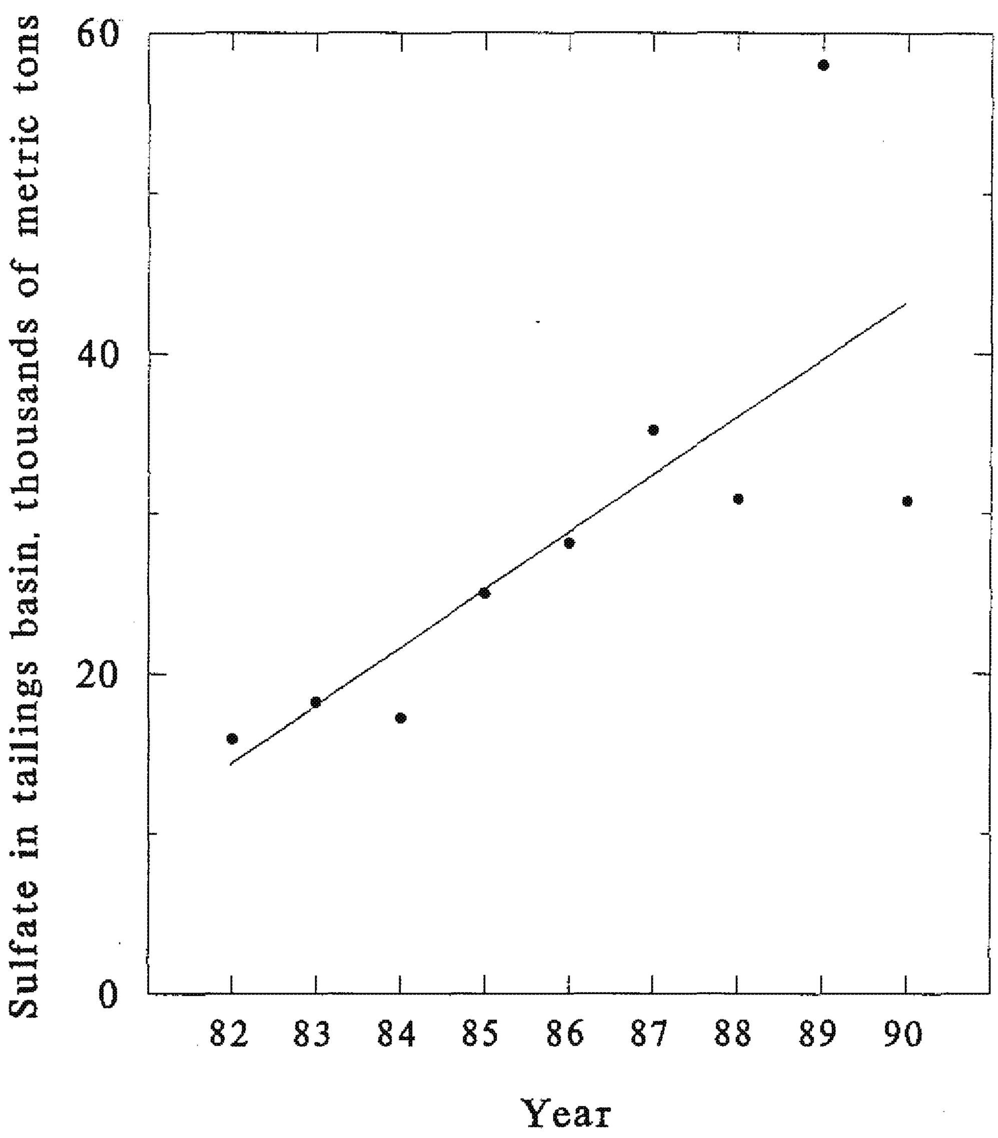

Table 1. Sulfate release to the Sand and Dark Rivers.

Site	Sand River at TH 53			Dark River at FR 271		
Initial Date	12/22/87	12/14/88	12/22/87	9/22/87	12/22/87	9/22/87
End Date	12/14/88	11/29/89	11/29/89	12/22/87	12/14/88	12/14/88
Time, Days	358	350	708	91	358	449
Sulfate, mg/L						
maximum	370	305	370	121	150	150
75%	180	210	210	113	110	110
median	120	155	130	110	79	88
25%	80	98	85	96	45	49
minimum	37	74	37	68	12	12
n	37	25	61	9	38	46
Flow, L/S						
maximum	1,300	1,700	1,700	470	2,200	2,200
75%	475	657	520	440	690	620
median	240	338	250	350	320	350
25%	160	202	170	280	220	240
minimum	1	85	1	260	28	28
n	37	24	61	8	35	42
mean	380	490	430	360	460	440
Mass Release						
Total, mt	1,360	1,940	3,300	310	1,360	1,670
Rate, mt/yr	1,390	1,960	1,670	1,240	1,390	1,360

n: number of samples

Table 2. Plant input solids from January 22 through February 16, 1990[1]

Input	Quantity mt	Sulfur Content pct	Sulfur Mass mt	Pct of Total input
Crude ore	3,477,154	0.092	3199	79
Dolomite/ Limestone	63,058	.034	22	0.5
Bentonite	7,949	.148	12	0.3
Total	3,548,161	NAp	3233	79.8

[1] Data from Brascugli, 1990 (Appendix 4).
NAp: not applicable

Table 3. Plant input water from January 22 through February 16, 1990[1]

Input	Quantity m^3	Sulfur Content ppm[2]	Sulfur Mass mt	Pct of Total input
Tailings basin return[3]	2,695,774	154	415	10
Make-up Water	1,831,334	84	154	3.8
Total	4,527,108	NAp	569	13.8

1 Data from Brascugli, 1990 (Appendix 4).
2 Concentration of sulfur present as sulfate.
3 Tailings basin return water volume calculated as the difference between output and make-up water volumes.
NAp: not applicable

Table 4. Plant input fuel and lubricant from January 22 through February 16, 1990[1].

Input	Quantity mt	Sulfur Content pct	Sulfur Mass mt	Pct of Total input
Natural gas	7275[2]	0.011[3]	80	2.0
Coal/Coke	7205	2.53	182	4.5
Wood	4616	.041	1.8	.04
Lubricant	55	.9	0.5	.01
Total	NAp	NAp	264	6.5

1 Data from Brascugli, 1990 (Appendix 4).
2 Million cubic meters
3 g/m^3
NAp: not applicable

Table 5. Plant output solids from January 22 through February 16, 1990[1].

Output	Quantity mt	Sulfur Content pct	Sulfur Mass mt	Pct of Total output
Pellets	812,351	0.0025	20	0.5
Fine tails	1,529,688	.079	1208	30
Coarse tails	1,019,791	.206	2101	52
Fugitive dust[1]	6.4	.22	< 0.01	0.4
Dust collectors[2]	< 0.1	.18	< .1	< .1
Agglomerator residue	4798	.31	15	.4
Concentrator residue	1742	.12	2	< .1
Coarse tail pocket residue	527	.27	2	< .1
Pellet stockpile residue	245	.11	< 1	< .1
Total	3,369,148	NAp	3348	83.3

1 From crude ore, pellets, and concentrate.
2 Dry dust collector at primary crusher and wet scrubbers throughout crushing, concentrator, and agglomerator plant.
NAp: not applicable

Table 6. Solids balance for USX plant from January 22 through February 16, 1990.

	Mass, mt	Sulfur mass, mt
Crude Ore	3,477,154	3,199
Dolomite/Limestone	63,058	22
Bentonite	7,949	12
Total Input	3,548,161	3,233
Pellets	812,351	20
Fine Tails	1,529,688	1,208
Coarse Tails	1,019,791	2,101
Fugitive Dust	6	< .01
Agglomerator Residue	4,798	15
Concentrator Residue	1,742	2
Coarse Tailing Pocket Residue	527	2
Pellet Stockpile Residue	245	< 1
Total Output	3,369,148	3,348

Table 7. Plant output water from January 22 through February 16, 1990[1].

Output	Quantity m^3	Sulfur Content[1] ppm	Sulfur Mass mt	Pct of Total output
Fine tailing water	2,021,493	148	299	7.3
Coarse tailing water	113,368	132	15	.4
Wet dust collector water	11,961	106	1	< .1
Agglomerator water	1,656,375	167	276	6.8
Concentrator water	513,028	142	73	1.8
Coarse tailing pocket water	53,170	146	8	.2
Pellet stockpile water	57,240	159	9	.2
Water with pellets	16,257	159(e)[2]	7(e)[2]	.2(e)[2]
Steam loss out stack	81,264	0(e)[2]	0(e)[2]	0 (e)[2]
Sewage treatment	2,952	95	< 1	0
Total	4,527,108	NAp	688	16.9

[1] Aqueous sulfur concentration occurring as sulfate.
[2] (e): estimated
NAp: not applicable

Table 8. Water balance for USX plant from January 22 through February 16, 1990.

	Volume, m^3	Sulfur mass, mt
Tailing Basin Return	2,695,774	415
Make-up Water	1,831,334	154
Total Input	4,527,108	569
Coarse Tailing Water	113,368	15
Fine Tailing Water	2,021,493	299
Wet Dust Collector Water	11,961	1
Agglomerator Water	1,656,375	276
Concentrator Water	513,028	73
Coarse Tailing Pocket Water	53,170	8
Pellet Stockpile Water	57,240	9
Water with Pellets	16,257	7
Steam Loss Out Stack	81,264	
Sewage Treatment Water	2,952	< 1
Total Output	4,527,108	688

Table 9. Fuel balance for USX plant for January 22 through February 16, 1990.

	Quantity, mt	Sulfur mass, mt
Natural Gas	7,275[1]	80
Coal/Coke	7,206	182
Wood	4,616	2
Total Input	NAp	264
Waste Gas (Total output)	679	40

[1] Million cubic meters
NAp: Not applicable

Table 10. Plant sulfur balance summary from January 22 through February 16, 1990[1].

	Sulfur input mt	Sulfur output mt	Sulfur output-Sulfur input mt
Pellet related solids	3233	3348	115
Water	569	688	119
Fuel	264	40	-224
Total	4066	4076	10

1 Data from Brascugli, 1990

Table 11. Calculation of sulfur transfer from fuel to water.

Calculation	Input Sulfur mt	Waste gas Sulfur, mt	Scrubber water sulfur, mt	Scrubber efficiency	Annual scrubber load, mt sulfur/year
1 [1]	264	145	119	45	1737
2 [2]	264	40	224	85	3270
3 [3]	264	204	60	23	876
4 [4]	264	198	66	25	964
5 [5]	264	188	76	29	1110
6 [6]	264	177	87	33	1270
7 [7]	264	132	132	50	1928

[1] Uses data from water balance.

[2] Uses measured waste gas scrubber output.

[3] Uses change in sulfate concentration and flow from scrubber.

[4] Assumes all sulfur present in fuel reports as waste gas, and 25 percent sulfur removal from waste gas by scrubber.

[5] Assumes all sulfur present in fuel reports as waste gas, and 29 percent sulfur removal from waste gas by scrubber.

[6] Assumes all sulfur present in fuel reports as waste gas, and 33 percent sulfur removal from waste gas by scrubber.

[7] Assumes all sulfur present in fuel reports as waste gas, and 50 percent sulfur removal from waste gas by scrubber.

Table 12. Sulfate mass in tailings basin.

	Cell 1			Cell 2			
Year	Volume m^3x10^6	$[SO_4]$ mg/L	Mass SO_4 mt	Volume m^3x10^6	$[SO_4]$ mg/L	Mass SO_4 mt	Total Mass SO_4 mt
1979	6.17			54.9			
1980	6.17			48.7			
1981	6.17			51.8			
1982	6.17			59.2	243	14,400	15,900 (e)
1983	6.17			58.6	282	16,500	18,237 (e)
1984	7.40			55.5	273	15,200	17,230 (e)
1985	7.40			64.1	350	22,400	24,990 (e)
1986	8.14	362	2950	78.9	320	25,200	28,150
1987	8.14	670[1]	5450	78.3	380	29,800	35,200
1988	8.51	244	2080	79.6	362	28,800	30,880
1989	8.88	448	3980	75.4	716[1]	54,000	57,980
1990	14.24 [2]	356	5070	72.9 [2]	353	25,700	30,790

(e): Estimated assuming the sulfate concentration in Cell 1 equalled that in Cell 2.

1 Anomalously high
2 Volume in 1981

Table 13. Sulfate input from Mountain Iron pit to tailings basin: 1981-1989.

Year	Flow $m^3 x 10^6$	SO_4[1] mg/L	Mass SO_4 T	Cumulative Mass SO_4, T
1981	8.82	198	1750	1750
1982	4.90	204	1000	2750
1983	2.38	211	502	3252
1984	2.60	217	564	3816
1985	9.36	223	2090	5906
1986	13.38	230	3080	8986
1987	3.30	236	779	9765
1988	13.78	242	3330	13,095
1989	9.78	249	2440	15,535

[1] Using $[SO_4]$ = 236 mg/L in 1987 and $\Delta [SO_4]/\Delta t$ = 6.37 mg/L-yr. The second value is the rate of increase from June 5, 1987 to February 5, 1990.

Table 14. Fuel Use at USX plant: 1981-1989

	Coal/Coke				Gas			Total SO_4	Cumulative	Cumulative
Year	Tons	Pcts	Tons S	Tons SO_4	$M^3 \times 10^6$	Tons S[1]	Tons SO^4	Tons	SO_4 Tons	SO_4 x 0.25
1981	75,933	0.66	501	1503	116,789	1289	3870	5370	5370	1340
1982	32,745	.67	219	657	12,587	139	417	1070	6440	1610
1983	65,947	1.25	824	2472	24,150	267	800	3270	9710	2430
1984	43,804	1.87	819	2457	43,999	486	1460	3920	13,630	3410
1985	53,035	1.96	1040	3120	40,902	452	1350	4470	18,100	4520
1986	26,669	2.73	728	2184	24,572	271	814	3000	21,100	5280
1987	3,985	2.74	109	327	47,633	526	1580	1910	23,010	5750
1988	25,227	2.60	656	1963	92,250	1018	3060	5030	28,040	7010
1989	16,174	2.61	422	1266	146,365	1616	4850	6120	34,160	8540

[1] Using sulfur content from Brascugli (1990) of 0.00481 grain/ft^3 = 0.011 g/m^3

Table 15. Pellet production, sulfate input to basin, and change in sulfate storage in tailings basin 1981-1989.

	PELLET PRODUCTION	INPUT FROM FUEL	INPUT FROM MT. IRON PIT	CHANGE IN BASIN STORAGE
	T X 10^6	T	T	T
1981	12.39	1340	1750	NAp
1982	3.27	268	1000	1800
1983	7.71	818	502	2300
1984	8.71	980	564	-1000
1985	9.91	1120	2090	7800
1986	5.62	748	3080	3200
1987	7.64	477	779	7000
1988	11.95	1260	3330	-4300
1989	12.29	1530	2440	27100

APPENDIX 1

Sulfate Concentration, Flow, and Sulfate Flux for the Sand and Dark Rivers

Table A1.1. Sulfate concentration, flow, and sulfate flux for the Sand River at TH53.

Mo	Da	Yr	SO_4 (mg/L)	S.C. (umho/cm)	Q (L/s)	SO_4 Flux (g/s)
3	4	87	250.0	850.	.	.
6	5	87	63.0	250.	.	.
6	18	87	57.0	270.	.	.
7	16	87	84.0	350.	.	.
8	18	87	110.0	410.	.	.
8	19	87	90.0	390.	.	.
9	22	87	83.0	370.	.	.
10	6	87	160.0	550.	.	.
10	22	87	120.0	440.	.	.
11	12	87	173.0	650.	.	.
11	18	87	60.0	405.	.	.
12	2	87	255.0	690.	.	.
12	10	87	230.0	770.	.	.
12	17	87	220.0	810.	.	.
12	22	87	340.0	1050.	170.	57.8
1	15	88	370.0	1100.	170.	62.9
1	21	88	370.0	1100.	96.	35.5
2	17	88	220.0	720.	162.	35.6
2	17	88	370.0	1200.	170.	62.9
3	2	88	350.0	1120.	124.	43.4
3	10	88	340.0	1100.	140.	47.6
3	16	88	340.0	1050.	123.	41.8
3	30	88	340.0	1000.	.	.
4	7	88	110.0	400.	.	.
4	14	88	75.0	280.	1105.	82.8
4	15	88	80.0	250.	1200.	96.0
4	22	88	84.0	290.	600.	50.4
4	28	88	85.0	280.	390.	33.1
5	5	88	76.0	280.	350.	26.6
5	12	88	37.0	250.	1100.	40.7
5	26	88	120.0	350.	470.	56.4
6	2	88	130.0	430.	310.	40.3
6	9	88	140.0	440.	250.	35.0
6	15	88	140.0	480.	240.	33.6
6	23	88	180.0	500.	200.	36.0
6	29	88	140.0	420.	160.	22.4
7	4	88	130.0	430.	66.	8.5
7	7	88	160.0	500.	150.	24.0
7	21	88	94.0	340.	6.	0.5
7	27	88	85.0	310.	1.	0.0

Table A1.1. Sulfate concentration, flow, and sulfate flux for the Sand River at TH53 (continued).

Mo	Da	Yr	SO_4 (mg/L)	S.C. (umho/cm)	Q (L/s)	SO_4 Flux (g/s)
8	11	88	98.0	280.	1000.	98.0
8	24	88	65.0	240.	1300.	84.5
8	30	88	63.0	210.	930.	58.5
9	7	88	55.0	250.	450.	24.7
9	21	88	60.0	240.	224.	13.4
10	5	88	77.0	270.	230.	17.7
10	19	88	73.0	180.	250.	18.2
11	2	88	120.0	370.	330.	39.6
11	17	88	120.0	370.	520.	62.4
12	2	88	.	.	480.	.
12	2	88	140.0	360.	475.	66.5
12	13	88	.	.	180.	.
12	14	88	180.0	470.	.	.
12	27	88	.	.	230.	.
12	28	88	190.0	470.	.	.
1	12	89	230.0	550.	200.	46.0
1	25	89	210.0	590.	193.	40.5
2	10	89	240.0	.	205.	49.2
2	22	89	245.0	.	200.	49.0
3	8	89	280.0	.	234.	65.5
3	22	89	255.0	.	538.	137.1
4	6	89	175.0	.	644.	112.7
4	19	89	74.0	.	760.	56.2
5	3	89	75.0	.	1010.	75.7
5	17	89	95.0	.	280.	26.6
5	31	89	79.0	.	1055.	83.3
6	15	89	75.0	.	1700.	127.5
6	28	89	95.0	.	670.	63.6
7	12	89	98.0	.	345.	33.8
7	26	89	123.0	.	140.	17.2
8	9	89	145.0	.	85.	12.3
8	23	89	175.0	.	114.	19.9
9	6	89	110.0	.	960.	105.6
9	20	89	168.0	.	410.	68.8
10	4	89	155.0	.	420.	65.1
10	18	89	155.0	.	330.	51.1
11	14	89	127.0	.	354.	44.9
11	29	89	305.0	.	236.	71.9

Table A1.2. Sulfate concentration, flow, and sulfate flux for the Dark River at FR 271.

Mo	Da	Yr	SO_4 (mg/L)	S.C. (umho/cm)	Q (L/s)	SO_4 Flux (g/s)
8	18	87	57.0	250.	.	.
9	22	87	68.0	265.	460.	31.2
10	6	87	110.0	365.	440.	48.4
10	22	87	93.0	330.	300.	27.9
11	12	87	100.0	345.	300.	30.0
11	19	87	116.0	340.	470.	54.5
12	2	87	121.0	360.	400.	48.4
12	10	87	110.0	340.	280.	30.8
12	17	87	110.0	410.	.	.
12	22	87	110.0	380.	260.	28.6
1	7	88	140.0	420.	200.	28.0
1	15	88	130.0	420.	.	.
1	21	88	120.0	430.	380.	45.6
1	29	88	150.0	450.	220.	33.0
2	3	88	130.0	460.	260.	33.8
2	17	88	51.0	260.	.	.
2	26	88	120.0	450.	240.	28.8
3	2	88	92.0	460.	220.	20.2
3	16	88	120.0	440.	300.	36.0
3	24	88	94.0	460.	270.	25.3
3	30	88	120.0	470.	280.	33.6
4	7	88	86.0	320.	1740.	149.6
4	13	88	82.0	320.	2140.	175.4
4	15	88	90.0	290.	1390.	125.1
4	22	88	110.0	420.	620.	68.2
4	28	88	32.0	180.	190.	6.0
5	5	88	95.0	390.	530.	50.3
5	12	88	78.0	350.	1000.	78.0
5	26	88	44.0	220.	300.	13.2
6	2	88	98.0	360.	320.	31.3
6	9	88	44.0	230.	140.	6.1
6	29	88	16.0	140.	110.	1.7
7	4	88	12.0	140.	55.	0.6
7	7	88	14.0	150.	72.	1.0
7	21	88	38.0	200.	220.	8.3
7	27	88	49.0	190.	28.	1.3
8	10	88	110.0	320.	1700.	187.0
8	24	88	63.0	200.	2200.	138.6
8	30	88	42.0	230.	1000.	42.0
9	7	88	54.0	220.	670.	36.1
9	21	88	35.0	140.	1000.	35.0

Table A1.2. Sulfate concentration, flow, and sulfate flux for the Dark River at FR 271 (continued).

Mo	Da	Yr	SO_4 (mg/L)	S.C. (umho/cm)	Q (L/s)	SO_4 Flux (g/s)
10	5	88	45.0	200.	520.	23.4
10	19	88	47.0	200.	450.	21.1
11	2	88	60.0	220.	490.	29.4
11	17	88	50.0	200.	.	.
12	2	88	80.0	240.	710.	56.8
12	14	88	76.0	240.	600.	45.6
12	28	88	75.0	260.	.	.
1	11	89	65.0	295.	600.	39.0
1	17	89	.	.	860.	.
1	25	89	72.0	300.	.	.
2	10	89	76.0	310.	.	.
3	22	89	.	.	250.	.
4	5	89	.	.	1920.	.
4	19	89	.	.	5000.	.
5	3	89	.	.	2060.	.
5	31	89	.	.	1730.	.
6	14	89	.	.	2680.	.
6	28	89	.	.	1080.	.
7	12	89	.	.	530.	.
7	26	89	.	.	230.	.
8	9	89	.	.	180.	.
8	23	89	.	.	120.	.
9	6	89	.	.	1600.	.
9	20	89	.	.	390.	.
10	4	89	.	.	560.	.
10	18	89	.	.	410.	.
11	14	89	.	.	560.	.
11	29	89	.	.	490.	.
12	13	89	.	.	370.	.
12	27	89	.	.	195.	.

APPENDIX 2

Sulfate Concentration, Flow, and Sulfate Flux for the Tailings Basin Seeps

Table A2.1. Sulfate concentration, flow, and sulfate flux at the East Toe Seep.

Mo	Da	Yr	SO_4 (mg/L)	S.C. (umho/cm)	Q (L/s)	SO_4 Flux (g/s)
10	22	84	290.0	790.	.	.
5	21	85	410.0	920.	.	.
8	27	85	420.0	1100.	.	.
11	8	85	280.0	1050.	.	.
8	19	87	605.0	1300.	.	.
11	4	87	280.0	1000.	.	.
11	18	87	470.0	1250.	.	.
12	2	87	370.0	850.	.	.
1	14	88	355.0	750.	.	.
2	17	88	390.0	750.	11.	4.6
2	25	88	.	1240.	13.	.
3	9	88	.	1140.	14.	.
3	23	88	360.0	1190.	14.	5.3
4	6	88	370.0	1160.	12.	4.5
4	20	88	380.0	1180.	11.	4.5
5	3	88	390.0	1140.	10.	4.1
5	18	88	410.0	1185.	11.	4.7
6	2	88	385.0	1200.	11.	4.2
6	15	88	380.0	1200.	11.	4.4
6	29	88	.	1200.	11.	.
7	14	88	360.0	1200.	11.	4.0
7	28	88	.	1175.	11.	.
8	11	88	335.0	900.	11.	3.9
8	24	88	400.0	1280.	16.	6.4
9	7	88	430.0	1290.	12.	5.3
9	21	88	410.0	1280.	11.	4.7
10	5	88	500.0	1310.	11.	5.9
10	19	88	430.0	1340.	12.	5.5
11	2	88	370.0	1300.	12.	4.6
11	17	88	370.0	1290.	13.	5.1
12	2	88	370.0	1270.	14.	5.2
12	13	88	400.0	1260.	14.	5.6

Table A2.1. Sulfate concentration, flow, and sulfate flux at the East Toe Seep (continued).

Mo	Da	Yr	SO_4 (mg/L)	S.C. (umho/cm)	Q (L/s)	SO_4 Flux (g/s)
1	11	89	365.0	1260.	14.	5.4
1	25	89	360.0	1210.	15.	5.4
2	15	89	330.0	1180.	8.	2.6
2	22	89	350.0	1180.	12.	4.4
3	8	89	380.0	1180.	12.	4.9
3	22	89	380.0	1160.	13.	5.0
4	5	89	380.0	1190.	11.	4.4
4	19	89	480.0	1190.	11.	5.7
5	3	89	440.0	1345.	13.	5.9
5	17	89	500.0	1410.	12.	6.3
5	31	89	480.0	1310.	11.	5.3
6	15	89	475.0	1300.	11.	5.4
6	28	89	.	1360.	10.	.
7	12	89	470.0	1310.	9.	4.5
7	26	89	410.0	1290.	10.	4.3
8	9	89	440.0	1250.	10.	4.7
8	23	89	480.0	1275.	10.	5.2
9	6	89	450.0	1260.	11.	5.3
9	20	89	475.0	1230.	12.	5.7
10	4	89	450.0	1260.	12.	5.4
10	18	89	440.0	1260.	12.	5.6
11	14	89	435.0	1240.	12.	5.2
11	29	89	425.0	1220.	13.	5.5

Table A2.2. Sulfate concentration, flow, and sulfate flux at the West Toe Seep.

Mo	Da	Yr	SO_4 (mg/L)	S.C. (umho/cm)	Q (L/s)	SO_4 Flux (g/s)
10	22	84	400.0	1200.	.	.
5	21	85	490.0	1300.	.	.
8	27	85	490.0	1290.	.	.
11	8	85	370.0	1250.	.	.
8	19	87	430.0	1200.	.	.
11	4	87	330.0	1100.	6.	2.2
11	18	87	430.0	1270.	6.	2.9
12	2	87	370.0	900.	5.	2.0
1	14	88	325.0	800.	5.	1.7
2	17	88	370.0	850.	6.	2.3
2	25	88	.	.	7.	.
3	9	88	.	1200.	5.	.
3	23	88	350.0	1185.	6.	2.1
4	6	88	360.0	1210.	5.	1.9
4	20	88	290.0	1290.	4.	1.2
5	3	88	405.0	1220.	4.	1.7
5	18	88	425.0	1220.	3.	1.4
6	2	88	365.0	1280.	2.	0.9
6	15	88	360.0	1290.	3.	1.1
6	29	88	.	1320.	3.	.
7	14	88	390.0	1190.	2.	0.9
7	28	88	.	1300.	2.	.
8	11	88	410.0	1100.	2.	0.9
8	24	88	430.0	1370.	2.	1.1
9	7	88	460.0	1470.	2.	1.2
9	21	88	455.0	1574.	2.	1.1
10	5	88	370.0	1640.	3.	1.1
10	19	88	590.0	1750.	2.	1.4
11	2	88	610.0	1820.	2.	1.5
11	17	88	370.0	1780.	2.	1.0
12	2	88	675.0	1740.	2.	1.6
12	13	88	705.0	1750.	2.	2.0

Table A2.2. Sulfate concentration, flow, and sulfate flux at the West Toe Seep (continued).

Mo	Da	Yr	SO_4 (mg/L)	S.C. (umho/cm)	Q (L/s)	SO_4 Flux (g/s)
1	11	89	720.0	1920.	6.	4.9
1	25	89	580.0	1700.	6.	3.8
2	15	89	620.0	1450.	5.	3.3
2	22	89	480.0	1420.	4.	2.3
3	8	89	520.0	1430.	4.	2.3
3	22	89	540.0	1450.	3.	2.0
4	5	89	590.0	1500.	5.	3.2
4	19	89	660.0	1610.	3.	2.5
5	3	89	680.0	1690.	3.	2.2
5	17	89	740.0	1760.	4.	3.2
5	31	89	760.0	1795.	4.	3.0
6	15	89	765.0	1820.	4.	3.0
6	28	89	.	1860.	3.	.
7	12	89	760.0	1860.	5.	3.9
7	26	89	750.0	1880.	3.	2.5
8	9	89	780.0	1860.	3.	2.8
8	23	89	830.0	1860.	2.	1.9
9	6	89	800.0	1960.	2.	2.3
9	20	89	800.0	1930.	2.	2.0
10	4	89	825.0	1960.	3.	2.7
10	18	89	820.0	1960.	3.	3.0
11	14	89	860.0	1940.	2.	2.3
11	29	89	875.0	1970.	2.	2.3

Table A2.3. Sulfate concentration at small seeps around the tailings basin in 1987.

Site	Mo	Da	Yr	SO_4 (mg/L)	S.C. (umho/cm)
SEEP020	8	18	87	560.0	1550.
SEEP090	6	10	87	740.0	1950.
SEEP100	6	10	87	740.0	1900.
SEEP200	6	10	87	740.0	1880.
SEEP200	6	10	87	740.0	1850.
SEEP205	6	10	87	450.0	1400.
SEEP210	6	10	87	1200.0	2550.
SEEP215	6	10	87	880.0	2200.
SEEP300	6	10	87	400.0	1300.
SEEP300	8	18	87	420.0	1260.
SEEP300	8	24	87	420.0	1260.
SEEP400	6	10	87	420.0	1300.
SEEP500	6	10	87	440.0	1250.
SEEP500	6	10	87	460.0	1270.
SEEP550	6	10	87	520.0	1400.
SEEP600	6	10	87	670.0	1700.

APPENDIX 3

Sulfate Concentrations in the Wells near the Tailings Basin

Table A3.1 Sulfate concentrations in wells near the tailings basin.

Site	Month	Day	Year	SO4	SC	Q	SO4 Flux
WELL1	9.000	25.000	1981.000	280.000	970.000	.	.
WELL1	12.000	21.000	1981.000	330.000	830.000	.	.
WELL1	4.000	30.000	1982.000	400.000	830.000	.	.
WELL1	7.000	29.000	1982.000	360.000	870.000	.	.
WELL1	10.000	21.000	1982.000	370.000	850.000	.	.
WELL1	5.000	12.000	1983.000	340.000	820.000	.	.
WELL1	7.000	26.000	1983.000	340.000	950.000	.	.
WELL1	11.000	1.000	1983.000	380.000	800.000	.	.
WELL1	6.000	22.000	1984.000	380.000	550.000	.	.
WELL1	10.000	22.000	1984.000	480.000	850.000	.	.
WELL1	5.000	21.000	1985.000	460.000	1000.000	.	.
WELL1	8.000	27.000	1985.000	430.000	1080.000	.	.
WELL1	11.000	8.000	1985.000	420.000	1100.000	.	.
WELL1	5.000	16.000	1986.000	530.000	890.000	.	.
WELL1	7.000	16.000	1987.000	440.000	1000.000	.	.
WELL1	10.000	14.000	1987.000	380.000	1010.000	.	.
WELL1	7.000	26.000	1988.000	370.000	.	.	.
WELL1	7.000	31.000	1989.000	460.000	.	.	.
WELL10	9.000	25.000	1981.000	12.000	156.000	.	.
WELL10	12.000	21.000	1981.000	13.000	165.000	.	.
WELL10	4.000	30.000	1982.000	18.000	83.000	.	.
WELL10	7.000	29.000	1982.000	11.000	140.000	.	.
WELL10	10.000	21.000	1982.000	10.000	150.000	.	.
WELL10	5.000	12.000	1983.000	11.000	91.000	.	.
WELL10	7.000	26.000	1983.000	6.000	98.000	.	.
WELL10	11.000	1.000	1983.000	5.000	95.000	.	.
WELL10	6.000	22.000	1984.000	8.500	61.000	.	.
WELL10	10.000	22.000	1984.000	16.000	92.000	.	.
WELL10	5.000	21.000	1985.000	20.000	65.000	.	.
WELL10	8.000	27.000	1985.000	10.000	99.000	.	.
WELL10	11.000	8.000	1985.000	9.800	165.000	.	.
WELL10	6.000	16.000	1986.000	14.000	80.000	.	.
WELL10	8.000	19.000	1987.000	50.000	195.000	.	.
WELL10	10.000	14.000	1987.000	25.000	170.000	.	.
WELL10	4.000	15.000	1988.000	72.000	110.000	.	.
WELL10	7.000	26.000	1988.000	25.000	.	.	.
WELL10	7.000	31.000	1989.000	12.000	.	.	.
WELL2	9.000	25.000	1981.000	240.000	1090.000	.	.
WELL2	4.000	30.000	1982.000	380.000	780.000	.	.
WELL2	7.000	29.000	1982.000	360.000	900.000	.	.
WELL2	10.000	21.000	1982.000	370.000	900.000	.	.
WELL2	5.000	12.000	1983.000	320.000	800.000	.	.
WELL2	7.000	26.000	1983.000	310.000	900.000	.	.
WELL2	6.000	22.000	1984.000	380.000	490.000	.	.
WELL2	10.000	22.000	1984.000	420.000	790.000	.	.
WELL2	5.000	21.000	1985.000	460.000	700.000	.	.
WELL2	8.000	27.000	1985.000	450.000	1090.000	.	.
WELL2	11.000	8.000	1985.000	440.000	1100.000	.	.
WELL2	5.000	16.000	1986.000	570.000	880.000	.	.
WELL2	8.000	19.000	1987.000	370.000	825.000	.	.
WELL2	10.000	14.000	1987.000	360.000	840.000	.	.
WELL2	7.000	26.000	1988.000	420.000	.	.	.
WELL2	7.000	31.000	1989.000	410.000	.	.	.
WELL3	9.000	25.000	1981.000	200.000	856.000	.	.
WELL3	12.000	21.000	1981.000	240.000	710.000	.	.
WELL3	4.000	30.000	1982.000	250.000	630.000	.	.
WELL3	7.000	29.000	1982.000	220.000	690.000	.	.
WELL3	10.000	21.000	1982.000	220.000	650.000	.	.
WELL3	5.000	12.000	1983.000	210.000	610.000	.	.
WELL3	7.000	26.000	1983.000	230.000	750.000	.	.
WELL3	11.000	1.000	1983.000	240.000	630.000	.	.

Table A3.1 (Continued)

Site	Month	Day	Year	SO4	SC	Q	SO4 Flux
WELL3	6.000	22.000	1984.000	310.000	470.000	.	.
WELL3	10.000	22.000	1984.000	320.000	600.000	.	.
WELL3	5.000	21.000	1985.000	270.000	500.000	.	.
WELL3	8.000	27.000	1985.000	280.000	830.000	.	.
WELL3	11.000	8.000	1985.000	260.000	875.000	.	.
WELL3	5.000	16.000	1986.000	430.000	610.000	.	.
WELL3	8.000	19.000	1987.000	290.000	970.000	.	.
WELL3	10.000	14.000	1987.000	270.000	985.000	.	.
WELL3	4.000	15.000	1988.000	290.000	1030.000	.	.
WELL3	7.000	15.000	1988.000	290.000	.	.	.
WELL3	5.000	15.000	1989.000	330.000	.	.	.
WELL4	9.000	25.000	1981.000	40.000	428.000	.	.
WELL4	12.000	21.000	1981.000	7.000	410.000	.	.
WELL4	4.000	30.000	1982.000	10.000	360.000	.	.
WELL4	7.000	29.000	1982.000	9.000	205.000	.	.
WELL4	10.000	21.000	1982.000	7.000	300.000	.	.
WELL4	5.000	12.000	1983.000	9.000	180.000	.	.
WELL4	7.000	26.000	1983.000	12.000	140.000	.	.
WELL4	11.000	1.000	1983.000	130.000	125.000	.	.
WELL4	6.000	22.000	1984.000	30.000	95.000	.	.
WELL4	10.000	22.000	1984.000	22.000	65.000	.	.
WELL4	5.000	21.000	1985.000	46.000	100.000	.	.
WELL4	8.000	27.000	1985.000	39.000	170.000	.	.
WELL4	11.000	8.000	1985.000	36.000	240.000	.	.
WELL4	5.000	16.000	1986.000	160.000	185.000	.	.
WELL4	8.000	19.000	1987.000	90.000	300.000	.	.
WELL4	10.000	14.000	1987.000	55.000	280.000	.	.
WELL4	4.000	15.000	1988.000	120.000	470.000	.	.
WELL4	7.000	15.000	1988.000	56.000	.	.	.
WELL4	5.000	15.000	1989.000	120.000	.	.	.
WELL5	9.000	25.000	1981.000	160.000	817.000	.	.
WELL5	4.000	30.000	1982.000	350.000	560.000	.	.
WELL5	7.000	29.000	1982.000	260.000	650.000	.	.
WELL5	10.000	21.000	1982.000	260.000	600.000	.	.
WELL5	5.000	12.000	1983.000	290.000	680.000	.	.
WELL5	7.000	26.000	1983.000	700.000	820.000	.	.
WELL5	11.000	1.000	1983.000	330.000	700.000	.	.
WELL5	6.000	22.000	1984.000	420.000	475.000	.	.
WELL5	10.000	22.000	1984.000	480.000	720.000	.	.
WELL5	5.000	21.000	1985.000	560.000	700.000	.	.
WELL5	8.000	27.000	1985.000	470.000	1060.000	.	.
WELL5	11.000	8.000	1985.000	460.000	950.000	.	.
WELL5	5.000	16.000	1986.000	640.000	830.000	.	.
WELL5	8.000	19.000	1987.000	60.000	1050.000	.	.
WELL5	10.000	14.000	1987.000	430.000	1100.000	.	.
WELL5	7.000	26.000	1988.000	420.000	.	.	.
WELL5	7.000	31.000	1989.000	524.000	.	.	.
WELL6	9.000	25.000	1981.000	150.000	195.000	.	.
WELL6	12.000	21.000	1981.000	39.000	170.000	.	.
WELL6	4.000	30.000	1982.000	76.000	200.000	.	.
WELL6	7.000	29.000	1982.000	100.000	230.000	.	.
WELL6	10.000	21.000	1982.000	100.000	300.000	.	.
WELL6	5.000	12.000	1983.000	150.000	379.000	.	.
WELL6	7.000	26.000	1983.000	160.000	450.000	.	.
WELL6	11.000	1.000	1983.000	180.000	395.000	.	.
WELL6	6.000	22.000	1984.000	230.000	320.000	.	.
WELL6	10.000	22.000	1984.000	270.000	500.000	.	.
WELL6	5.000	21.000	1985.000	290.000	400.000	.	.
WELL6	8.000	27.000	1985.000	310.000	800.000	.	.
WELL6	11.000	8.000	1985.000	300.000	900.000	.	.
WELL6	5.000	16.000	1986.000	510.000	890.000	.	.

Table A3.1 (Continued)

Site	Month	Day	Year	SO4	SC	Q	SO4 Flux
WELL6	8.000	19.000	1987.000	460.000	900.000	.	.
WELL6	10.000	14.000	1987.000	460.000	950.000	.	.
WELL6	4.000	15.000	1988.000	470.000	1210.000	.	.
WELL6	7.000	15.000	1988.000	420.000	.	.	.
WELL6	5.000	15.000	1989.000	540.000	.	.	.
WELL7	9.000	25.000	1981.000	110.000	895.000	.	.
WELL7	12.000	21.000	1981.000	53.000	1130.000	.	.
WELL7	4.000	30.000	1982.000	850.000	1370.000	.	.
WELL7	7.000	26.000	1982.000	900.000	1580.000	.	.
WELL7	7.000	29.000	1982.000	900.000	.	.	.
WELL7	10.000	21.000	1982.000	910.000	.	.	.
WELL7	5.000	12.000	1983.000	1000.000	.	.	.
WELL7	7.000	26.000	1983.000	1130.000	.	.	.
WELL7	11.000	1.000	1983.000	1200.000	1650.000	.	.
WELL7	6.000	22.000	1984.000	1300.000	1200.000	.	.
WELL7	10.000	22.000	1984.000	820.000	1420.000	.	.
WELL7	5.000	21.000	1985.000	1200.000	1400.000	.	.
WELL7	8.000	27.000	1985.000	1000.000	1850.000	.	.
WELL7	11.000	8.000	1985.000	1030.000	1900.000	.	.
WELL7	6.000	16.000	1986.000	85.000	1100.000	.	.
WELL7	8.000	19.000	1987.000	510.000	1425.000	.	.
WELL7	10.000	14.000	1987.000	605.000	1450.000	.	.
WELL7	4.000	15.000	1988.000	520.000	1360.000	.	.
WELL7	7.000	15.000	1988.000	450.000	.	.	.
WELL7	5.000	15.000	1989.000	670.000	.	.	.
WELL8	9.000	25.000	1981.000	110.000	895.000	.	.
WELL8	12.000	21.000	1981.000	105.000	780.000	.	.
WELL8	4.000	30.000	1982.000	51.000	700.000	.	.
WELL8	7.000	29.000	1982.000	110.000	700.000	.	.
WELL8	10.000	21.000	1982.000	79.000	650.000	.	.
WELL8	5.000	12.000	1983.000	65.000	610.000	.	.
WELL8	7.000	26.000	1983.000	61.000	720.000	.	.
WELL8	11.000	1.000	1983.000	48.000	600.000	.	.
WELL8	6.000	22.000	1984.000	92.000	420.000	.	.
WELL8	10.000	22.000	1984.000	100.000	620.000	.	.
WELL8	5.000	21.000	1985.000	140.000	420.000	.	.
WELL8	8.000	27.000	1985.000	240.000	860.000	.	.
WELL8	11.000	8.000	1985.000	230.000	850.000	.	.
WELL8	6.000	16.000	1986.000	160.000	650.000	.	.
WELL8	8.000	19.000	1987.000	210.000	950.000	.	.
WELL8	10.000	14.000	1987.000	160.000	930.000	.	.
WELL8	4.000	15.000	1988.000	160.000	1200.000	.	.
WELL8	7.000	15.000	1988.000	240.000	.	.	.
WELL8	5.000	15.000	1989.000	310.000	.	.	.

Table A3.1 (Continued)

Site	Month	Day	Year	SO4	SC	Q	SO4 Flux
WELL9	9.000	25.000	1981.000	11.000	117.000	.	.
WELL9	12.000	21.000	1981.000	4.000	70.000	.	.
WELL9	4.000	30.000	1982.000	1.000	52.000	.	.
WELL9	7.000	29.000	1982.000	2.000	50.000	.	.
WELL9	10.000	21.000	1982.000	1.000	45.000	.	.
WELL9	5.000	12.000	1983.000	1.000	42.000	.	.
WELL9	7.000	26.000	1983.000	1.000	50.000	.	.
WELL9	11.000	1.000	1983.000	1.000	45.000	.	.
WELL9	6.000	22.000	1984.000	0.800	29.000	.	.
WELL9	10.000	22.000	1984.000	0.600	45.000	.	.
WELL9	5.000	21.000	1985.000	0.300	30.000	.	.
WELL9	8.000	27.000	1985.000	0.500	34.000	.	.
WELL9	11.000	8.000	1985.000	1.200	80.000	.	.
WELL9	6.000	16.000	1986.000	0.500	35.000	.	.
WELL9	8.000	19.000	1987.000	30.000	45.000	.	.
WELL9	10.000	14.000	1987.000	9.000	140.000	.	.
WELL9	4.000	15.000	1988.000	62.000	69.000	.	.
WELL9	7.000	15.000	1988.000	15.000	.	.	.
WELL9	5.000	15.000	1989.000	0.500	.	.	.

APPENDIX 4

Sulfur Balance in the Plant
Conducted by USX

USS
Minnesota Ore Operations
P. O. Box 417
Mt. Iron, MN 55768

08/02/1990

Anne Jagunich
DNR - Division of Minerals
P.O. Box 567
Hibbing, MN 55746

Subject: Sulfate Study for NPDES Permit MN 0057207

Dear Anne:

Attached is the report submitted to the MPCA on a month-long study of Sulfur Balances for the period January 22 through February 16, 1990 we discussed on 8-01-90. In scanning this report, I realize that it probably is not all the information you are looking for. I also understand the time frame you are working within. Despite all this, I am forwarding it to you since it is the only data compiled as of this date. Compiling additional information will of course require more time. I will discuss the situation here with the appropriate people and will expect to hear from you.

JMHartley

Jane M. Hartley
Environmental Engineering

Attachment

cc: N.A. Brascugli

Plant

USS
Minnesota Ore Operations
P. O. Box 417
Mt. Iron, MN 55768

June 15, 1990

Mr. D. A. Hall
Supervisor, Permits Unit
Division of Water Quality
Minnesota Pollution Control Agency
520 Lafayette Road
St. Paul, MN 55155

Re: NPDES/SDS Permit MN0057207
Study of Sulfate Sources

Dear Mr. Hall,

We hereby submit for your review and approval the final report on the study of sulfate sources as required by the subject permit, Part I.C.9 and your letter dated January 4, 1988.

This study was conducted during the period January 22 through Feberuary 16, 1990 with the Step III Agglomerator facility (Lines 6 & 7) fueled with a coal/petroleum coke blend. Both lines operated continuously throughout the test period.

Should you have any further questions on this matter, please call Ms. Jane Hartley at (218) 749-7532 or my office at (218) 749-7485.

Yours truly,

N Brascugli

N. A. Brascugli
Manager-Technical Services

NAB/jem

Attachment

cc J. M. Hartley
W. E. Snee

USS A DIVISION OF USX CORPORATION
MINNTAC PLANT- SULFUR BALANCE
NPDES PERMIT NO. MN 0057207

PNT NO.	MATERIAL DESCRIPTION	QUANTITY	AS	SULFUR (S.) AVG	AS	TOTAL S.	AS
	INPUTS:						
1	CRUDE ORE	3832867	N.T.	0.092	%	3526.2376	N.T./MO
2	MK-UP WATER	483840000	GAL	253	PPM	170.0704	N.T./MO
3	NATURAL GAS	256916	MCF	0.00481	gr/cu ft	16.2909	N.T./MO
4	WOOD	5088	N.T.	0.041	%	2.0861	N.T./MO
5	COAL/COKE	7943	N.T.	2.53	%	200.9579	N.T./MO
6	BENTONITE	8762	N.T.	0.148	%	12.9678	N.T./MO
7	T.B. RET WATER (68?,273,208)	1394796000	GAL	461	PPM	893.3427	N.T./MO
8	DOLOM/LIMESTONE	69509	N.T.	0.034	%	23.6331	N.T./MO
9	R&M MAT (LUBE)	61.08	N.T.	0.9	%	0.5497	N.T./MO
	TOTAL INPUTS					4846.1361	N.T./MO
	OUTPUTS:						
10	FUGITIVE DUST:						
	CRUDE ORE	0.56	N.T.	0.178	%	0.0010	N.T./MO
	PELLET	1.64	N.T.	0.002	%	0.0000	N.T./MO
	CONCENTRATE	5.12	N.T.	0.012	%	0.0006	N.T./MO
11	STEP I W.G.	244.72	N.T.	3.52	%	8.6141	N.T./MO
12	STEP II W.G.	467.1	N.T.	3.52	%	16.4419	N.T./MO
13	STEP III W.G.	37.21	N.T.	51.07	%	19.0031	N.T./MO
14	CRUDE ORE D C	0.08	LB/NT PLT	0.178	%	0.0001	N.T./MO
15	AGGLOM D C	0.01	LB/NT PLT	0.0115	%	0.0000	N.T./MO
15.1	WET D C WATER EM	3160000	GAL	318	PPM	1.3961	N.T./MO
16	COARSE TAILS	1124116	N.T.	0.206	%	2315.6790	N.T./MO
17	FINE TAILS						
	SOLIDS	1686175	N.T.	0.079	%	1332.0783	N.T./MO
	WATER	534080000	GAL	445	PPM	330.1967	N.T./MO
18	SEW. TRTMN'T PLT	780000	GAL	285	PPM	0.3088	N.T./MO
19	OUTFALLS/LIQUIDS:						
19.0	NE ST III PLT ST	48384	GAL	469	PPM	0.0370	NT/MO
19.1	N ST III PLT ST	15074397	GAL	476	PPM	9.9690	NT/MO
19.2	N ST III AGG	158876414	GAL	564	PPM	124.4930	NT/MO
19.3	N ST II AGG	155423246	GAL	479	PPM	103.4327	NT/MO
19.4	NW ST I AGG	123315832	GAL	447	PPM	76.5831	NT/MO
19.6	N ST II CONC	46249055	GAL	427	PPM	27.4370	NT/MO
19.7	N ST II CRS TL PKT	7616892	GAL	442	PPM	4.6774	NT/MO
19.8	N ST I CONC	44030284	GAL	426	PPM	26.0596	NT/MO
19.9	N ST III CONC	45262935	GAL	422	PPM	26.5376	NT/MO
19.10	N ST III CRS TL PKT	6430769	GAL	432	PPM	3.8597	NT/MO

19	OUTFALLS /SOLIDS:						
19.0	NE ST III PLT ST	0	N.T.			0.0000	NT/MO
19.1	N ST III PLT ST	270.17	N.T.	0.108	%	0.2918	NT/MO
19.2	N ST III AGG	1191.95	N.T.	0.49	%	5.8406	NT/MO
19.3	N ST II AGG	2915.12	N.T.	0.167	%	4.8682	NT/MO
19.4	NW ST I AGG	1182.15	N.T.	0.465	%	5.4970	NT/MO
19.6	N ST II CONC	925.28	N.T.	0.061	%	0.5644	NT/MO
19.7	N ST II CRS TL PKT	514.30	N.T.	0.259	%	1.3320	NT/MO
19.8	N ST I CONC	844.18	N.T.	0.089	%	0.7513	NT/MO
19.9	N ST III CONC	150.92	N.T.	0.603	%	0.9101	NT/MO
19.10	N ST III CRS TL PKT	67.01	N.T.	0.371	%	0.2486	NT/MO
20	INCL. IN 19						
21	INCL. IN 19						
22	INCL. IN 19						
23	PELLETS	895454	N.T.	0.0025	%	22.3864	NT/MO
	TOTAL OUTPUTS					4469.4965	NT/MO

SULFUR BALANCE DIFFERENTIAL = 4846.1361 - 4469.4965 376.6396 N.T.

SULFUR BALANCE % ERROR = 7.77 %

USS, A DIVISION OF USX CORPORATION
MINNTAC PLANT - FLOW SHEET SCHEMATIC
SULFUR BALANCE TEST POINTS

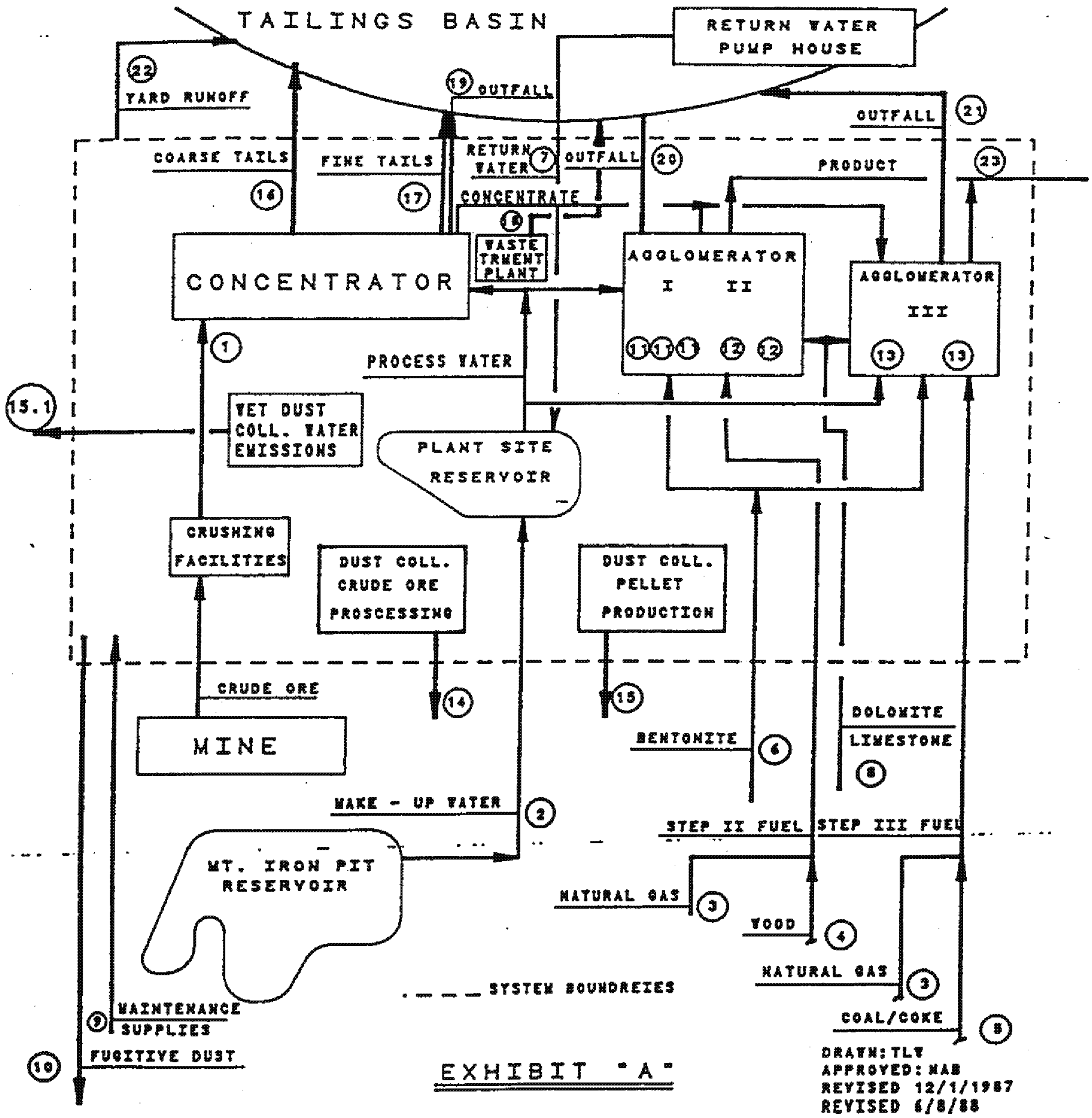

EXHIBIT "A"

DRAWN: TLW
APPROVED: NAB
REVISED 12/1/1987
REVISED 6/8/88

Sulfur Balance Study
1 Month Period - January 21st - February 17, 1990

General Notes:

Sulfur Dioxide Emission Test 1/25/90 Line 7

Test Run	Concentration (ppm,w)	Emission Rate (LB/HR)
1/1	6	22
1/2	7	28
1/3	8	30
Avg.	7	27

Step II W. G. Sulfur rates based on 9/3/87 stack test.

Step I W. G. Sulfur rates based on 7/21/80 stack test.

Agglomerator operating hours during test period:

Step I	650.03
Step II	873.17
Step III	1308.02

Fine tails solids = 43% by weight

Where samples were N.A. on weekends, daily averages were used.

USS/USX CORPORATION
MINNESOTA ORE OPERATIONS
QUALITY ASSURANCE LABORATORY

1990 MPCA SULFUR BALANCE STUDY
OF MINNTAC
JANUARY 22 - FEBRUARY 16, 1990

SAMPLE	SAMPLING FREQUENCY	SAMPLE VOLUME	COMPOSITE PERIOD
Rod Mill Water	Daily	1 liter	Weekly
Concentrator Thickener O'flow	Daily	1 liter	Weekly
Agglomerator Return Water	Daily	1 liter	Weekly (also % solids)
Scrubber Input Water	Daily	1 liter	Weekly
Scrubber Output Water	Daily	1 liter	Weekly (also % solids)
Turn Bin O'flow	Daily	1 liter	Weekly (also % solids)
Turn Bin U'flow	Daily	1 liter	Weekly (also % solids)
Crusher 1/2 Dust	Weekly	100 grams	Month
Crusher 3/4 Dust	Weekly	100 grams	Month
Agglom2 Dust	Daily	1 liter	Weekly (also % solids)
Agglom3 Dust	Daily	1 liter	Weekly (also % solids)
Coarse Tails	Usual	Usual	Daily
Fine Tails Solids	Usual	Usual	Day and Month
Fine Tails Water	Each Sample	125 ml	Daily
Water from NOLA 2 Audits	Each audit	125 ml	Daily to Weekly
Water from NOLA 3 Audits	Each audit	125 ml	Daily to Weekly

satcal/ABCDE

ss:csl/MPCADT

USS/USX CORPORATION
MINNESOTA ORE OPERATIONS
QUALITY ASSURANCE LABORATORY

1990 MPCA SULFUR BALANCE
OF MINNTAC
JAN 22 - FEB 16. 1990

	Week of January 22, 1990			Week of January 28, 1990			Week of February 4, 1990			Week of February 11, 1990		
Sample ID	Water SO4=	% Solids	Solids % S	Water SO4=	% Solids	Solids % S	Water SO4=	% Solids	Solids % S	Water SO4=	% Solids	Solids % S
Rod Mill Water	439	0		433	0		433	0		426	0	
Concentrator Thickener O'flow	460	0		419	0		419	0		438	0	
Agglomerator Return Water	490	.11	.042	471	.09	.038	417	.04	.064	478	.14	.058
Scrubber Input Water	438	0		427	0		420	0		452	0	
Scrubber Output Water	679	.01	.032	669	.02	NS	623	.06	.174	653	.07	.044
Turnbin O'flow	426	.04	.124	419	.13	.124	419	.09	.136	438	.13	.160
Turnbin U'flow	433	1.06	.078	423	1.51	.090	422	1.05	.092	441	1.35	.164
Agglom 2 Dust	485	.25	.006	474	.27	.006	494	.71	.006	513	1.09	.005
Agglom 3 Dust	528	.38	.011	525	.44	.009	510	.45	.012	522	.45	.014
Concentrate Flow to Agglom 2	465		.009	445		.009	431		.010	448		.008
Concentrate Flow to Agglom 3	463		.008	431		.008	421		.008	459		.009
Mt. Iron Pit Reservoir	241	0		235	0		248	0		289	0	
Clearwater Reservoir Tailings Basin Return	472	0		462	0		487	0		421	0	
Step 3 Concentrator Floor Wash & Sewer	420	.17	.220	414	.04	1.290	430	.04	.260	423	.08	.645
Sewage Treatment Plant Effluent	281	0		287	0		294	0		278	.02	NS
Process Water from Plant Site Res.	430	0		412	0		431	0		423	0	

satcal/MPCADT

USS/USX CORPORATION
MINNESOTA ORE OPERATIONS
QUALITY ASSURANCE LABORATORY

1990 MPCA SULFUR BALANCE
OF MINNTAC
JAN 22 - FEB 16, 1990

Sample ID	Week of January 22, 1990 Water SO4=	% Solids	Solids % S	Week of January 28, 1990 Water SO4=	% Solids	Solids % S	Week of February 4, 1990 Water SO4=	% Solids	Solids % S	Week of February 11, 1990 Water SO4=	% Solids	Solids % S
Step 1 Concentrator Floor Wash & Sewer	422	.33	.080	418	.25	.102	428	.99	.096	434	.26	.076
Coarse Tailings 1&2 Floor Wash & Sewer	436	1.38	.212	430	1.08	.170	451	1.62	.174	451	2.40	.480
Step 2 Concentrator Floor Wash & Sewer	415	.16	.056	429	.34	.058	427	.33	.056	438	1.09	.072
Storm Sewer NW of Step 1 Agglom & Pellet Loadout	454	.41	.338	447	.25	.264	440	.16	.506	445	.08	.750
Agglom 2 Floor Wash & Storm Sewer	459	.73	.174	478	.25	.200	493	.49	.160	487	.34	.132
Step 3 Coarse Tails Pocket Floor Wash & Storm Sewer	427	.24	.350	436	.34	.350	426	.16	.355	437	.25	.430
Agglom 3 Floor Wash & Storm Sewer	570	.24	.506	574	.08	.590	556	.24	.425	554	.16	.440
Pipe North of Step 3 Pellet Stockpile, Sump Discharge	479	.49	.06	470	.17	.164	482	.66	.074	474	.41	.132
Culvert N.E. of Step 3 Pellet Stockpile	496	0		492	0		418	0		NS	NS	
Wood			.040			.039			.043			.043
Pellets			.003			.002			.002			.003

Rod Mill Feed Total Test Period Sulfur--> 0.092%

Bentonite Total Test Period Sulfur--> 0.149%

Limestone/Dolomite Total Test Period Sulfur--> 0.034%

Primary Crusher Baghouse Dust Collector Total Test Period Sulfur--> 0.217%

satcal/MPCADT

USS/USX CORPORATION
MINNESOTA ORE OPERATIONS
QUALITY ASSURANCE LABORATORY

1990 MPCA SULFUR BALANCE
OF MINNTAC
JAN 22 - FEB 16. 1990

Daily Analyses

Day	Coal/Coke	Coarse Tailings	Fine Tailings
1-22-90	2.59	.220	.134
1-23	2.62	.170	.074
1-24	2.49	.136	.042
1-25	2.54	.206	.052
1-26	2.63	.202	.080
1-27	2.73	NS	NS
1-28	2.50	NS	NS
1-29	NS	.186	.080
1-30	3.04	.188	.070
1-31	2.57	.160	.068
2-01	2.83	.152	.066
2-02	2.90	.178	.068
2-03	2.61	NS	NS
2-04	2.55	NS	NS
2-05	2.40	.228	.072
2-06	2.40	.236	.086
2-07	2.12	.272	.104
2-08	2.33	.186	.096
2-09	2.38	NS	NS
2-10	2.20	NS	NS
2-11	2.48	.230	.084
2-12	2.53	.208	.078
2-13	2.57	.296	.094
2-14	2.66	.264	.090
2-15	2.38	.222	.070
2-16	2.29	.180	.062

APPENDIX 5

Sulfate Concentration in the
Tailings Basin

Table A5.1 Sulfate concentrations (mg/L) and specific conductance (umbo/cm) in the tailings basin.

SITE	YEAR	MONTH	DAY	SO_4	SC
CELL1	1986	5	6	355	460
CELL1	1986	7	6	370	925
CELL1	1987	10	14	670	.
CELL1	1988	7	26	244	.
CELL1	1989	5	16	485	.
CELL1	1989	7	31	460	.
CELL1	1989	10	26	400	.
CELL1	1990	5	8	340	.
CELL1	1990	7	25	360	.
CELL1	1990	10	16	360	.
CELL2	1983	7	26	219	790
CELL2	1983	11	1	267	680
CELL2	1984	6	22	246	420
CELL2	1984	10	22	318	800
CELL2	1985	5	21	256	380
CELL2	1985	8	27	290	880
CELL2	1985	11	8	504	800
CELL2	1986	5	6	690	500
CELL2	1987	7	6	305	950
CELL2	1987	10	14	390	.
CELL2	1988	7	26	362	.
CELL2	1989	7	31	754	.
CELL2	1989	10	26	750	.
CELL2	1990	5	8	340	.
CELL2	1990	7	25	360	.
CELL2	1990	10	16	360	.